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# The Head Posture of Helicopter Pilots during Visual Flight: A New Hypothesis for the Head Tilt Associated with Banking Aircraft

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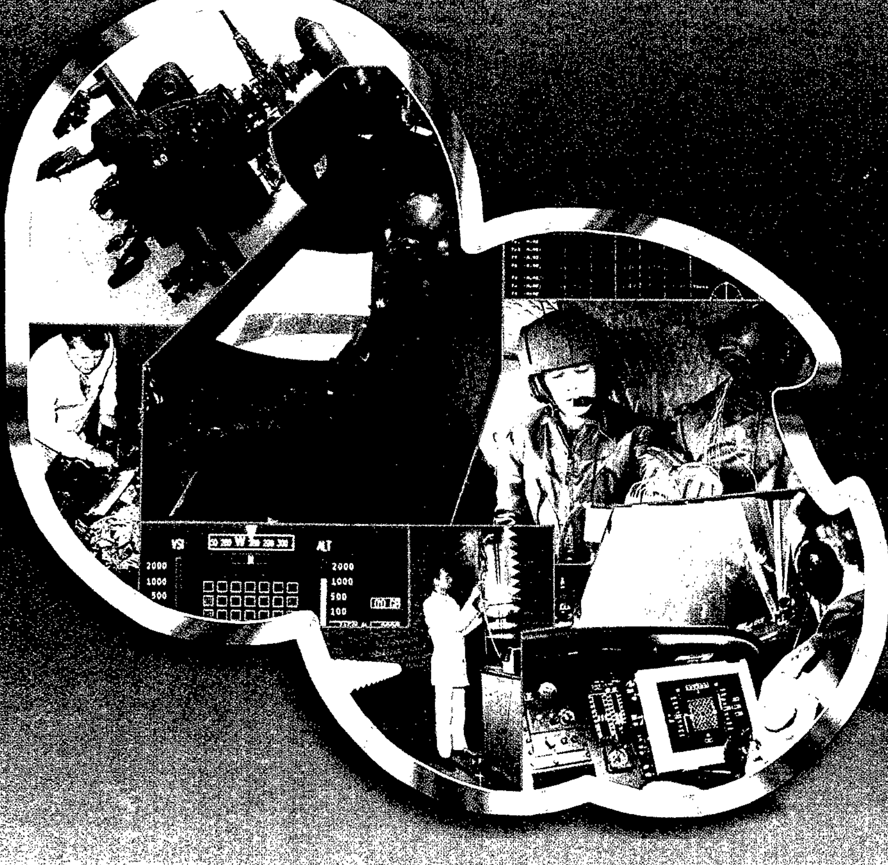

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13. ABSTRACT *(Maximum 200 words)*
Head azimuth, pitch, and lateral tilt of four pilots controlling a Lynx helicopter through multiple slalom maneuvers under visual flight conditions are reported and analyzed. Pilot A performed the maneuver 11 times, Pilot B performed it 12 times, Pilot C performed it 8 times, and Pilot D performed it 12 times. The specifics of the slalom maneuver, two 90° right turns followed by two 90° left turns, are unambiguously reflected in the head motions. As the aircraft turned twice to the right then twice to the left, the head turned twice to the right then twice to the left, presumably to enable the pilot to see where the aircraft was going. Head azimuth was highly correlated with head tilt: When the head turned to the right, it tilted to the left; and when the head turned to the left, it tilted to the right. Furthermore, the correlation between head tilt and pitch was highly reliable: When the head tilted either to the left or to the right, it pitched up. On the other hand, the correlation between azimuth and pitch was inconsistent and variable. The pattern of reliable correlations among head posture suggests mechanisms that might help explain the opto-kinetic cervical reflex.

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## Table of contents



## List of figures

Table of contents (continued)
List of figures (continued)

Page

Table of contents (continued)
List of figures (continued)

Page

Table of contents (continued)
List of figures (continued)



List of tables

## Introduction

Nearly thirty years ago, during test flights to evaluate the design of aircraft instruments, Hasbrook and Rasmussen (1973) reported an anecdotal observation about a pattern of head movements that seemed characteristic of the test pilots. They noted "... there is some indication that holding the head straight with the airplane, while making shallow or median banked turns with reference to the real horizon, may be psychologically unnatural. Our personal observation of head movements of pilots during performance of such ground-oriented maneuvers as 'eights around a pylon' and 'S-turns over a road' shows that many pilots subconsciously keep their heads normal to the real horizon." Hasbrook and Rasmussen further noted "... this holding the head (and therefore the plane of the eyes) normal to the horizon regardless of tilting of the body is also evident among ice skaters, skiers, and motorcyclists when they tilt their bodies from side to side during serpentine maneuvers."

Nearly 20 years later, this phenomenon was studied in a series of flight tests with 14 U. S. Air Force instrument pilot volunteers flying a visual, non-motion, 180° dome flight simulator (Patterson, 1995). This study used a standard, commercial, off-the-shelf head tracker to measure the left and right head tilts as the pilots executed a prescribed flight plan. A principal goal of the study was to measure the relationship between the pilots' head tilt and the tilt of the horizon caused by aircraft bank. The flight plan consisted of several flight tasks. One task, executed under visual flight conditions, required multiple left and right aircraft banks.to fly to successive visual waypoints. This task obviously caused the horizon, which was visible outside the cockpit, to bank as the aircraft banked, but, of course, in opposite direction. Head tilt was found to be a statistically significant function of aircraft bank angle. Specifically, for aircraft bank angles of about between $\pm 35°$ (where negative indicates an aircraft bank to the left and positive indicates an aircraft bank to the right), the head was found to tilt to a maximum of about $\pm 15°$ (where negative indicates a tilt to the left and positive indicates a tilt to the right). The head follows the horizon in this relationship; when the aircraft banks to the left, causing the visual horizon to appear to bank to the right, the pilot's head tilts to the right so that the head remains approximately perpendicular to the visible horizon. When the aircraft banks to the right, causing the visual horizon to appear to bank to the left, the pilot's head tilts to the left so that the head remains approximately perpendicular to the visible horizon in this situation as well. This relationship between aircraft bank and head tilt appears to be approximately linear for the central $\pm 35°$ to 40° of aircraft bank angle, producing a maximum head tilt of $\pm 15°$. Beyond an aircraft bank angle of about 40°, head tilt remains approximately asymptotic for aircraft bank angles to about $\pm 70°$. For aircraft bank angles beyond $\pm 70°$, there is some evidence that head tilt seems to decrease slightly.

The dependence of head tilt on aircraft bank angle and/or the apparent banking of the horizon under visual flight conditions has been demonstrated in a number of subsequent studies and has been called the opto-kinetic cervical reflex or OKCR. For example, OKCR has been demonstrated in the Army's UH-60 helicopter simulator (Braithwaite et al., 1997a, b) as well as in high performance aircraft (Merryman, 1997; Merryman and Cacioppo, 1997). The OKCR has been demonstrated not only in pilots

but also in aircrew performing tasks similar to those of a navigator (Smith, 1994, 1997). Based on theoretical arguments, the OKCR was expected to depend on the size of the pilot's field of view; but this prediction has only marginally been supported by comparisons across different studies (Gallimore et al., 1999, 2000).

The OKCR is described as an essentially involuntary neck reflex that is driven to a great extent by appropriate visual stimulation primarily of the peripheral visual field. (Patterson, 1995; Patterson et al., 1997; Previc, 2004). According to this model, the purpose of OKCR is to help stabilize the horizon in such a way that the horizon provides a primary reference through the fovea and across the horizontal meridian of the visual field. Rotation of the relevant visual stimuli causes the head to tilt reflexively in the same direction as the stimulus rotation. This model goes beyond the simple observation that the head tilts with aircraft bank angle. The model asserts that: (1) the head tilt is a visually driven reflex, (2) the reflex is strongest to stimuli in the visual periphery, (3) the reflex serves the specific purpose of providing a stabilized horizontal frame of reference, and (4) such a reference is important for spatial orientation.

Several investigators have argued that the head tilt phenomena may have important implications for unresolved questions concerning the design of aircraft attitude indicators (Ercoline, DeVilbiss, and Evans, 2004; Patterson, 1995; Smith, 1994; Smith, 1997; Patterson et al.; 1997). These questions derive from a controversy concerning fundamental ambiguities inherent in the design of current attitude indicators. Specifically, the question concerns choosing between either the design in which the horizon icon moves relative to the fixed aircraft icon, a design that is often referred to in the literature as the 'inside-out' attitude display, or the design in which the aircraft icon moves relative to the fixed horizon icon, the design referred to as the 'outside-in' attitude display (Johnson and Roscoe, 1972).

Since the attitude indicator is mounted on the instrument panel, its orientation and position remain constant in the aircraft cockpit. The head tilt phenomena, occurring during an aircraft banking turn that produces the apparent tilt of the real horizon visible outside the cockpit, may cause the pilot's head to change orientation between the real horizon outside the cockpit and the attitude indicator's horizon icon visible inside the cockpit. This differential head orientation to the two different representations of horizon information may create the potential for confusion, a confusion that may be compounded when attitude indicators are included on head mounted displays (HMDs). The head tilt may make the interpretation of an HMD attitude indicator problematic (Jennings et al., 1998). Consequently, the implications that head tilt may have for the design of aircraft attitude indicators need to be considered, particularly for newly emerging HMD technology.

HMDs are devices or systems that present a pilot with imagery, flight information, and/or fire control (weaponry) imagery and symbology (Rash, 1999). These devices are, by definition, head- or helmet-mounted systems that include, at a minimum, "an image source and collimating optics in a head mount" (Melzer and Moffitt, 1997). Usually an HMD system includes a visually coupled component to slave head and/or eye

positions and motions to one or more of the aircraft systems (Rash, 1999). Examples of rotary-wing HMDs include the U.S. Army's fielded Integrated Helmet and Display Sighting System (IHADSS) used on the AH-64 Apache attack helicopter.

Virtually all HMD systems currently track only head azimuth and head pitch; however, there is a growing interest in adding head tilt to provide 3-axis tracking and control. This would provide the capability of keeping HMD imagery aligned with the aircraft structure (Task and Kocian, 1995). This availability for head tilt compensation may be an advantage and could reduce workload. Haworth has argued that as HMDs achieve wider fields of view, the displayed imagery becomes more compelling and may require such tilt compensation (Haworth, 1997). Although U. S. Army AH-64 Apache aviators have informally stated that they would not like the addition of tilt compensation (Rash, 1999), others found that tilt compensation in HMD systems reduced pilot workload and motion sickness during critical flight periods where pilot workload already may be high (Craig, Jennings, and Swail, 2000). A much earlier study found that any rotary-wing aircraft maneuver that caused the weapon-aiming HMD sighting image to roll as the head tilted resulted in considerable tracking/aiming performance degradation (Michael, Jardine, and Goom, 1978).

The tilting of the pilot's head associated with aircraft banking may be important for the design and use of attitude indicators and HMDs. The present paper provides a hypothesis for the observed head tilting behavior that is an alternative to the conventional OKCR explanation. This alternative hypothesis suggests that at least some head tilting with aircraft bank angle is not a reflex driven by stimuli in the peripheral visual field. If the proposed alternative hypothesis is true, it suggests that a substantial reconsideration of the stimuli driving OKCR is in order. It also suggests that the observed head tilt may have purposes other than to improve "spatial awareness by establishing the horizon retinal image as a stabilized primary visual–spatial cue" (Gallimore et al., 1999). The hypothesis presented in the present paper is based on data from studies that were designed to address completely unrelated research issues. It may be noted that these data were obtained from test pilots controlling a rotary-wing aircraft in actual flight; whereas, most of the data leading to the conventional OKCR model had been collected from pilots in flight simulators.

The database used in the present report was obtained during the Day/Night All Weather (D/NAW) program conducted from the mid to late 1990s by the Defence Evaluation and Research Agency (DERA), Farnborough, United Kingdom. The principal aim of this program was to enable safe tactical helicopter flight in severely limited visibility. The major focus of the program was advanced helmet- mounted or HMD technologies and the associated symbology design issues (Crowley, 1998) and had nothing to do with the study of OKCR.

From March to September 1997, under the auspices of the D/NAW program, a series of flights was flown to establish baseline flight performance for future HMD performance comparisons. These flights consisted of several flight path maneuvers (e.g., slalom, rapid egress, side-step, etc.). As an adjunct to the normal flight performance

parameters measured during the flights, head azimuth, pitch, and tilt also were collected, not as part of the experimental design, but as standard practice. These head posture data were made available for analysis through a collaboration agreement between DERA and the U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama under the auspices of the Technical Cooperative Program (TTCP).

Thorough descriptions of head azimuth, head pitch, and head tilt components of this database are available from previous publications; however, these descriptions addressed each of these three components of head posture independently of each other (Rostad et al., 2001, 2003; Rostad, Rash, and Crowley, 2003; Stelle et al., 2003a, b). The reports did not provide any information concerning the relationships or dependencies among head azimuth, pitch, or tilt; nor were the data put in the context of the OKCR. The present paper reports analysis of the interdependencies among head azimuth, pitch, and tilt recorded during flight under meteorological conditions of good daytime of visibility. The relationship among these three head posture parameters suggested the biomechanical hypothesis of head tilting that is presented here as an alternative, or at least a supplement, to the conventional view that the head tilt is a reflex in response to appropriate visual stimuli. Despite the undeniable operational importance of pilot head movements and HMDs, the literature contains surprisingly few analyses of the relationships among head azimuth, pitch, and tilt during flight.

## Methods

The flights consisted of six flight maneuvers executed at one of two levels of aggressiveness (LOAs). A full flight was approximately 90 minutes in duration and consisted of a number of "runs" where a "run" was defined as the completion of the full set of all six maneuvers at a given LOA by the pilot. The number of runs in each flight varied depending upon a variety of conditions. The test pilots were familiar with the flight area. Head tracking data were collected on all flights. The present paper discusses only observations made during slalom maneuvers executed under meteorological conditions that provided an environment of good daytime visibility. Full descriptions of all the instrumentation, visual environments, and flight maneuvers are provided elsewhere (Rostad et al., 2001, 2003; Rostad, Rash, and Crowley, 2003; Stelle et al., 2003a, b).

### Instrumentation

All flights were in an AH Mk 7 Lynx helicopter that was modified for research purposes. The automatic flight control system (AFCS) was switched on during all flights to improve aircraft handling by damping aircraft fluctuations. The AFCS provided pitch, roll, and yaw rate damping; and pitch and roll attitude hold (although pilots tended not to use roll attitude hold). The Lynx also was modified to incorporate a visually coupled head tracking system.

The aircraft was configured for two experimenters who sat in the rear cabin, the subject pilot who sat in the front left seat and the safety pilot who sat in the front right seat. The subject pilot was provided with a cut-down panel with only the primary flight instruments.

The HMD's Visually Coupled System incorporated a direct current electromagnetic head positioning system (HPS) which provided a six-degree of freedom output. A pair of bore sight reticule units was associated with the HPS and permitted the subject pilot to align the system at start-up. The HPS sampled head position approximately every 5 milliseconds (ms), but the available head position data files had been transformed to 100 ms (0.1 sec) samples to reduce the volume of data for storage and analysis.

## Subjects

Four volunteer pilots participated in this study. Pilot A was 37 years old with 2700 flight hours; Pilot B was 31 years old with 1500 hours; Pilot C was 34 years old with 2000 hours; and Pilot D was 33 with 1830 hours. Pilot A was a U.S. Army exchange test pilot; the other pilots were British Army test pilots.

## Flight maneuvers

Each pilot flew six maneuvers: slalom, curved approach, hovering (spot) turns, rapid egress, bob-up/down, and sidestep. All six maneuvers were performed successively in each run, starting with the slalom and ending with the sidestep maneuver. The present paper examines the slalom maneuver because it has the most consistent flight pattern and easily defined flight cycle.

Flights occurred in the region of southern United Kingdom known as Haxton Down, part of the Salisbury Plain training area, approximately 6.6 miles (11 kilometers) north of the Boscombe Down airfield. The safety pilot aligned the aircraft over the track and handed the controls over to the subject pilot at an appropriate ground speed, at 50 feet above ground level (AGL), and at a point at least 650 feet (200 m) prior to the first slalom turn. Ground speed at release was approximately 30 knots for low LOA and 40 knots for moderate LOA. The moderate LOA was to be completed within 90 seconds but there were no such time constraints for the low LOA.

The slalom segment of the test course consisted of a South to North transit through the Haxton Down area at nap-of-the-earth heights. At Haxton Down, a convenient group of South-North oriented woods labeled Woods One through Four provided a serpentine (slalom) course, which had been developed into a variant of the Aeronautical Design Standards (ADS)-33 slalom Mission Task Elements (MTEs) (see Figure 1). The MTEs started at a ground speed appropriate to the LOA and ended at any suitable exit speed.

Slalom maneuver

Previously published reports described the slalom maneuver as consisting of time history data collected over a flight pattern flown over a set course running North and South with the turns going East and West (Figure 1). Analysis was confined to a defined section within the slalom maneuver. This section, referred to as a cycle, was defined as shown in Figure 2. A cycle consisted of two right-hand turns followed by two left-hand turns. Small portions before and after the turns were included in order to capture pilot head movements during preparation for and recovery from the turns. In order to do this consistently, the mean was calculated from the minimum and the maximum of the longitude values. The point where the longitude exceeded the mean before the first left-hand turn was considered the start point of the cycle. The point where the longitude fell below the mean after the last right-hand turn was considered the end point of the cycle.

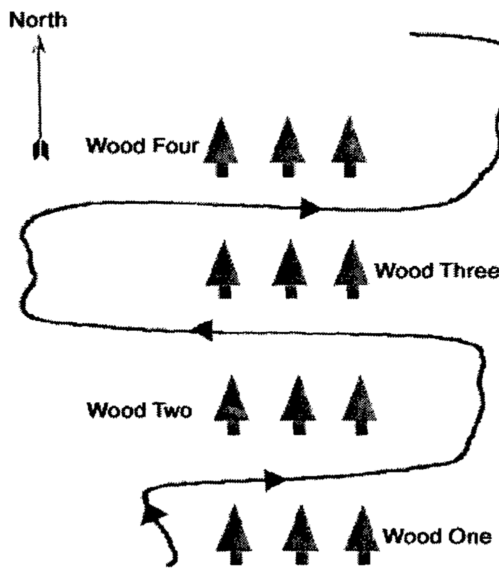



Figure 1. Representative flight path for the slalom flight maneuver.

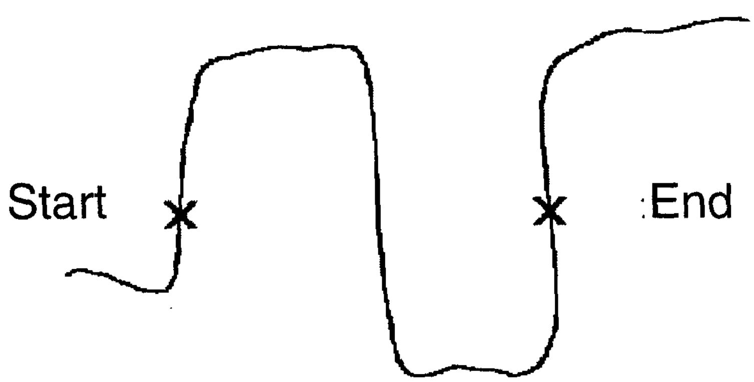



Figure 2. Definition of cycle used in analysis to define the slalom maneuver consisting of a pair of right turns followed by a pair of left turns.

Slalom database

The database consisted of a set of files where each file contained data for a single slalom flight for a single pilot. The files for each of the four pilots were identified and sorted, and the files for each of the flights conducted in the good visual environment were identified. A total of 11 slalom flights were identified for Pilot A, 12 slalom flights for Pilot B, 8 slalom flights for Pilot C, and 11 slalom flights for Pilot D.

Each file contained three fields. The first field contained head azimuth; the second field contained head pitch, and the third field contained head tilt; all of which were in degrees and all of which were sampled synchronously at 10 Hz (100-ms intervals). Since this sampling rate was constant, the number of data points in the file coded the length of time required to complete that execution of the slalom. From the number of data points, it was determined that each pilot had a group of slalom flights that required about 70-seconds and another group that required about 45-seconds to complete. These two groups of flights were the low and moderate LOAs, respectively.

Results

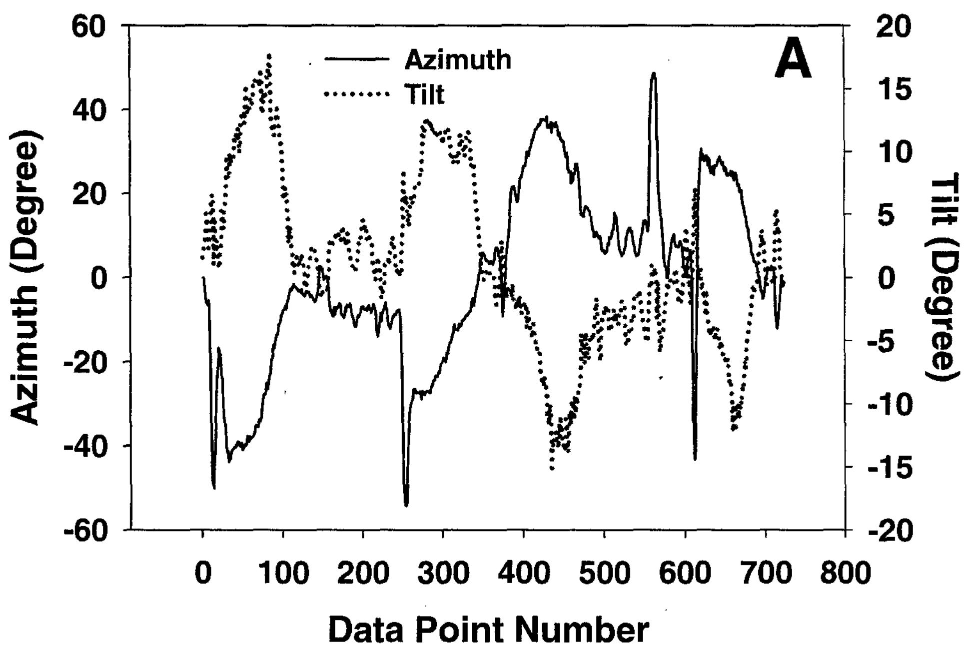



Figure 3. Head azimuth on the left ordinate and head tilt on the right ordinate, both in degrees, as a function of time (10 datapoints = 1 second) for Pilot A's first slalom.

Pilot A's head azimuth and head tilt recorded during Pilot A's first slalom are in Figure 3. Head azimuth, shown as the solid line, is referenced to the left ordinate, which is scaled in degrees. Positive degrees indicate that the head was turned toward the right

while negative degrees indicate that the head was turned toward the left with respect to the straight ahead zero calibration. Head tilt, shown as the dotted line, is referenced to the right ordinate, which is also scaled in degrees. Positive degrees of head tilt indicate that the top of the head was tilted toward the right while negative degrees indicate that the top of the head was tilted toward the left with respect to the vertical calibration. The abscissa shows the number of successive data points. Since the data were plotted with a sampling rate of 10 Hz, the abscissa provides time scale; 10 successive data points is one second.

Figure 3 shows that it took Pilot A about 72.4-seconds to complete this slalom since 724 data points are plotted on the abscissa. As described in the Methods section, the slalom maneuver required two successive 90° left turns followed by two successive 90° right turns for a total of 360°, with each turn separated by a segment of straight flight. Since standard rate turns require 120 seconds to complete the 360° (3°/sec), the rate of turn for each 90° component of the slalom was likely far steeper than the standard 3°/sec. If coordinated flight is assumed, bank angles were calculated to be between 15° and 35°.

The time scale on the abscissa relates the pilot's head tracking data to the execution of the slalom. The first left turn is reflected in the excursion of head azimuth from 0° to about -40° for data points between about 20 to about 90, indicating a head turn to the left that lasted approximately 7 seconds. The data suggest that this left head turn was preceded by a brief head turn, or glance, to the left that occurred over data points from about 10 to about 20, which may reflect an anticipatory or preparatory head check of about 1-sec total duration. By data point 110, the head had returned to near 0° (straight ahead) and remained there for about 12 seconds; that is, until about data point 240. From about data point 240 to about 260, the head turned to the left by about 60° for about 1-second. This 1-second, 60° turn of the head to the left was followed by a left head turn to about 30° that was held until approximately data point 285, after which the head gradually turned forward toward 0°.

Similarly, the two right turns of the slalom are indicated by the two right turns of the head, the first began with approximately data point 400, reaching a maximum value of about 40° and returning toward 0° near data point 500. The second right head turn began near data point 625, reached a maximum value of about 25°, and returned toward 0° near data point 700.

The relationship between head azimuth and head tilt

Figure 3 shows that head tilt is closely related to head azimuth, but the two tend to be out of phase with each other; when the pilot turns to the left, the head tilts to the right, and when the pilot turns to the right, the head tilts to the left. The range of the observed head tilt covers about ±15°, exactly the values expected from the OKCR literature.

Pilot A executed the slalom 11 times, but the head azimuth and head tilt data recorded during only the first flight are shown in Figure 3. Appendix A catalogues the head azimuth and head tilt recorded for each of Pilot A's 11 slalom flights, in the format

of Figure 3. For the sake of completeness, Figure 3 is included in the Appendix as the upper part of Appendix A Figure A-1. Appendix B presents the head azimuth and head tilt obtained during Pilot B's 12 slalom flights; Appendix C presents the head azimuth and head tilt obtained during Pilot C's 8 slaloms; and Appendix D presents the head azimuth and head tilt obtained during Pilot D's 11 slaloms. The inverse relationship between head azimuth and tilt is apparent in all the flights of these four pilots.

Figure 4 is a scattergram of head tilt against head azimuth collapsed across all 11 of Pilot A's flights. This figure, displaying 5,820 individual data points, shows that most of the data tends to be in the central 30° of azimuth. The figure also shows that the relationship between head azimuth and tilt is described by a cloud or distribution with a roughly sigmoid shape. The correlation coefficient calculated for these data points is -0.7773.

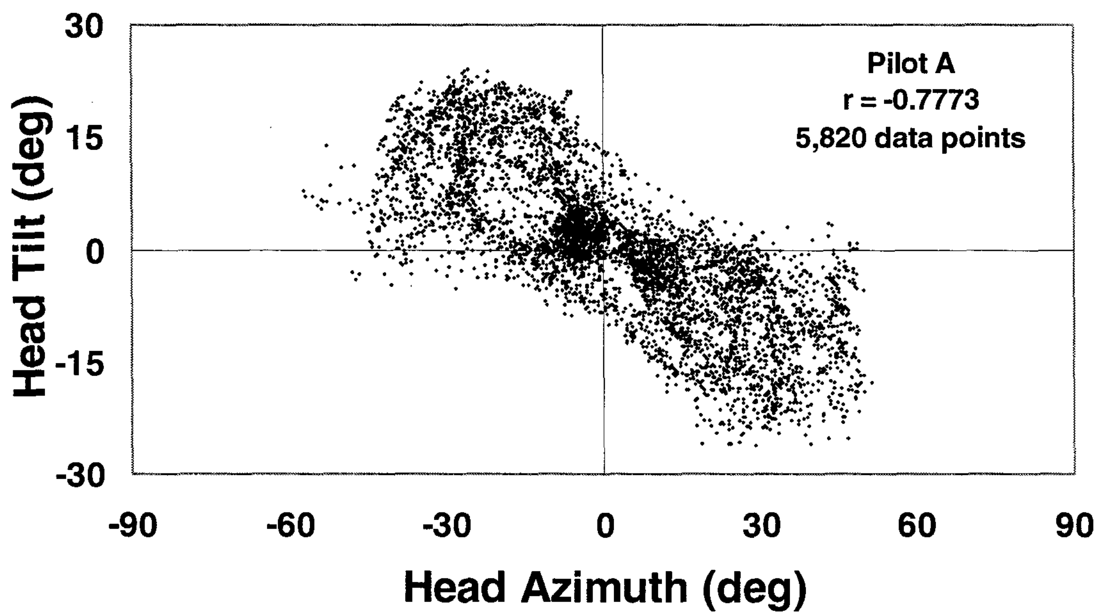



Figure 4. Scattergram of head tilt against head azimuth, both in degrees, for all Pilot A's slaloms.

Plotting data in this fashion not only eliminates all sequential information, it collapses the data across all flights, ignoring the distinction between low and moderate LOA. Previous analysis of this database found no evidence for differences between the low and moderate LOA flights (Rostad et al., 2001, 2003; Rostad, Rash, and Crowley, 2003; Stelle et al., 2003a, b). These previous reports assessed head azimuth, pitch, and tilt individually. The present report, addressing correlations and dependencies among these three aspects of head posture, specifically assessed whether LOA affected relationships among head azimuth, pitch, and tilt. Formal statistical tests were routinely performed to assess the null hypothesis that the two levels of LOA were not statistically different and no consistent convincing evidence was found for differences between the

two LOA levels. Consequently, the analyses in the present paper collapse across LOA levels.

Figure 5 is a comparable scattergram of head tilt against head azimuth collapsed across all 12 of Pilot B's flights. This figure, plotting 6,777 data points, shows the same general pattern as does Figure 4. The data are distributed in a roughly sigmoidal fashion with most of the data tending to be in the central 30° of azimuth. The calculated correlation coefficient between Pilot B's head tilt and head azimuth is r = -0.7771. Figure 6 is the scattergram of Pilot C's 4,804 head tilt and head azimuth data points; the calculated correlation for these data is -0.6709. Similarly, Figure 7 is the scattergram of Pilot D's 6,468 head tilt and head azimuth data points with a calculated correlation coefficient of -0.6075.

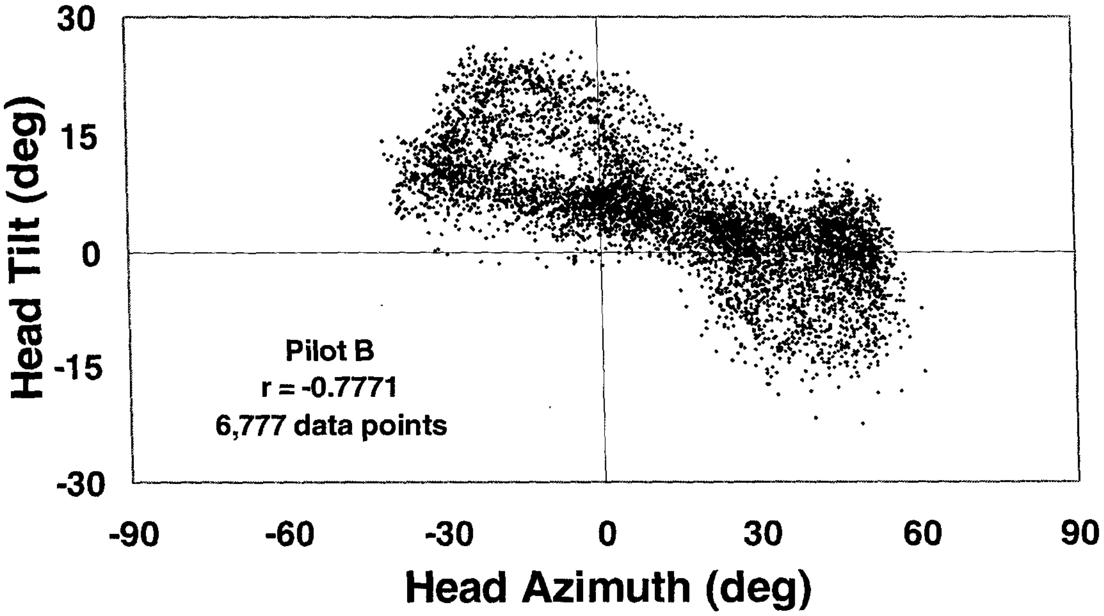



Figure 5. Scattergram of head tilt against head azimuth, both in degrees, for all Pilot B's slaloms.

Figures 4 through 7 not only show a consistent, substantial, negative correlation between head azimuth and head tilt, they also suggest that a plot of head tilt as a function of head azimuth would resemble the plot of head tilt as a function of aircraft bank angle that is typically described in the literature as characteristic of the OKCR. Since aircraft bank angle, like head azimuth, is a continuous variable, most OKCR studies aggregate bank angle into discreet 5° bins, and calculate the average head tilt for each bin. Figure 8 provides a comparable graph of the head tilt data that were presented in Figure 4. Figure 8, plotting average head tilt as a function of head azimuth, approximate the shape of the graphs routinely presented in the literature as characteristic of OKCR. Head tilt is roughly linear in its middle section, is negatively correlated with azimuth, asymptotes with head tilts of about $\pm 15°$, and suggests a decrease in head tilt for the extreme azimuths. The error bars for each average in Figure 8 are $\pm 1.0$ standard deviation.

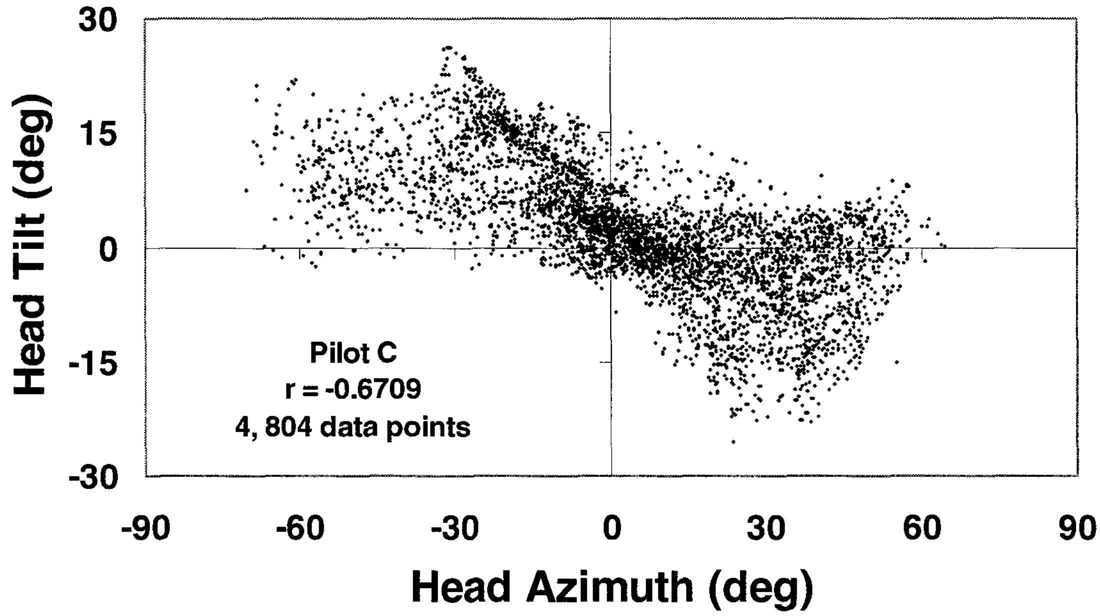



Figure 6. Scattergram of head tilt against head azimuth, both in degrees, for all Pilot C's slaloms.

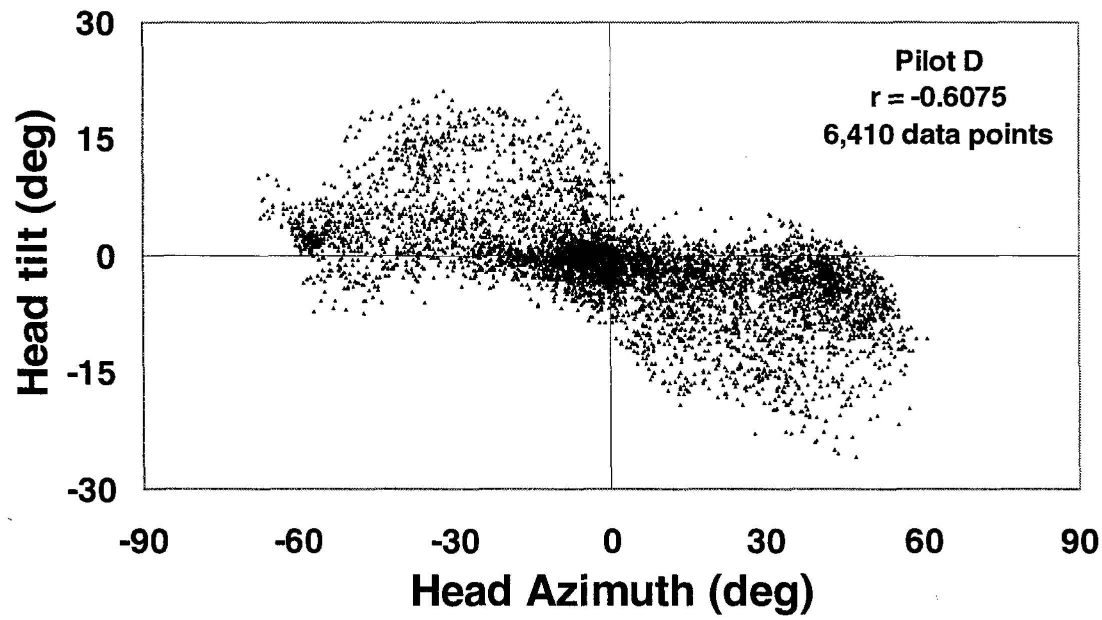



Figure 7. Scattergram of head tilt against head azimuth, both in degrees, for all Pilot D's slaloms.

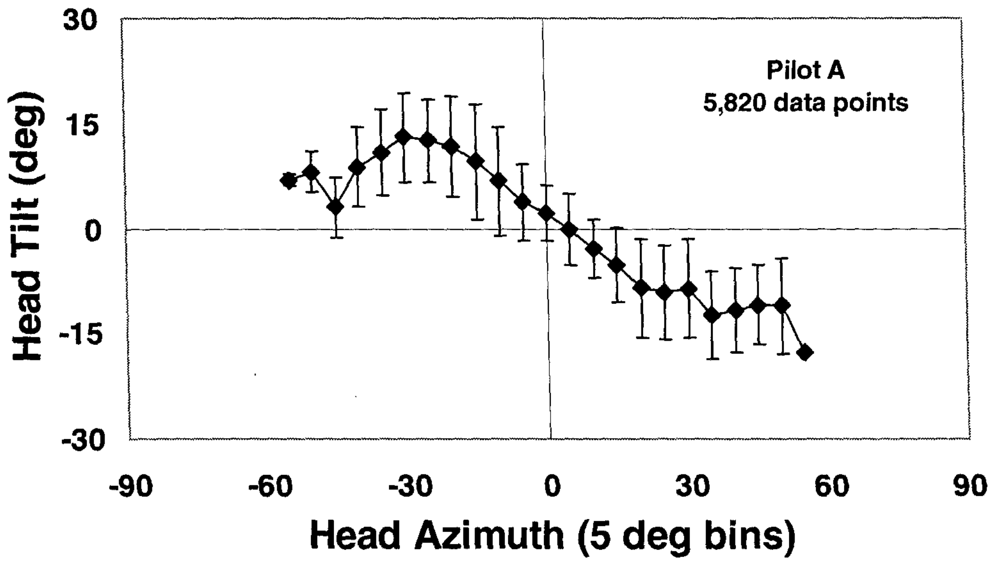



Figure 8. Head tilt average (with $\pm$ 1.0 S.D.) as a function of head azimuth averaged across all Pilot A's eleven slaloms. Means and S.D. were calculated for the head tilts that were aggregated in azimuth bins of 5° widths.

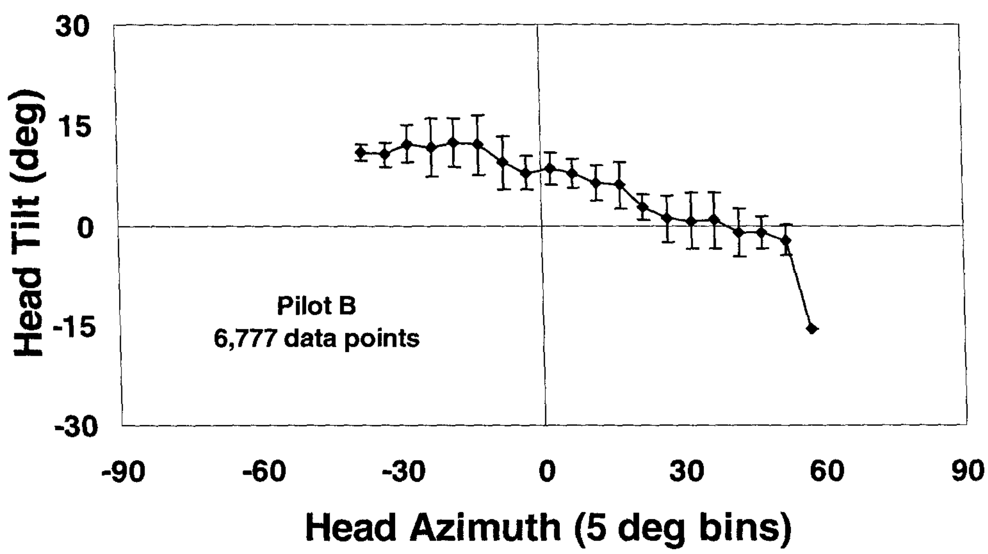



Figure 9. Head tilt average (with $\pm$ 1.0 S.D.) as a function of head azimuth averaged across all Pilot B's twelve slaloms. Means and S.D. were calculated for the head tilts that were aggregated in azimuth bins of 5° widths.

The same methods used to generate Figure 8 for Pilot A were used to generate average head tilt as a function of binned head azimuth shown in Figure 9 for Pilot B, Figure 10 for Pilot C, and Figure 11 for Pilot D. Each of these figures lists the number of

repeated slalom flights each pilot flew, as well as the number of data points used for each figure. These figures show the consistency of the relation between head azimuth and tilt.

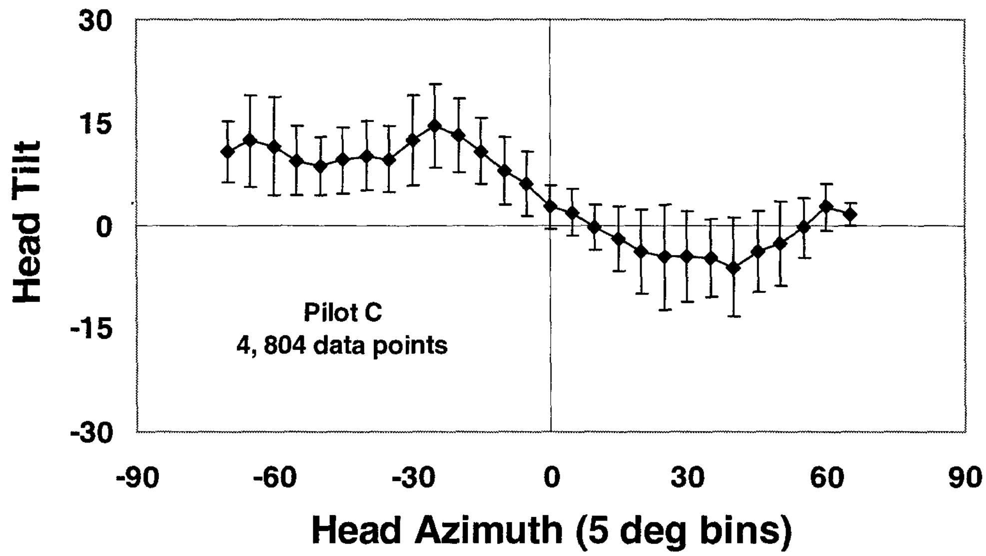



Figure 10. Head tilt average (with $\pm$ 1.0 S.D.) as a function of head azimuth averaged across all Pilot C's eight slaloms. Means and S.D. were calculated for the head tilts that were aggregated in azimuth bins of 5° widths.

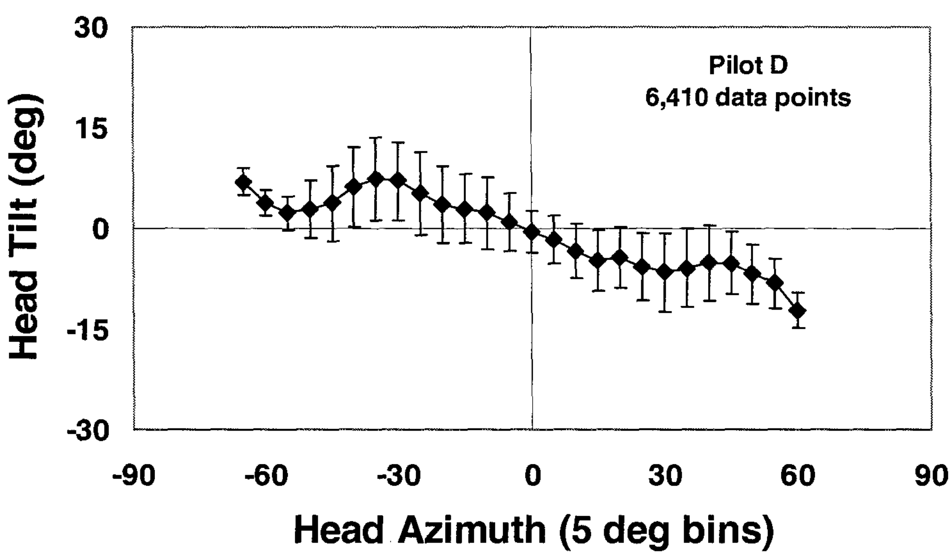



Figure 11. Head tilt average (with $\pm$ 1.0 S.D.) as a function of head azimuth averaged across all Pilot D's eleven slaloms. Means and S.D. were calculated for the head tilts that were aggregated in azimuth bins of 5° widths.

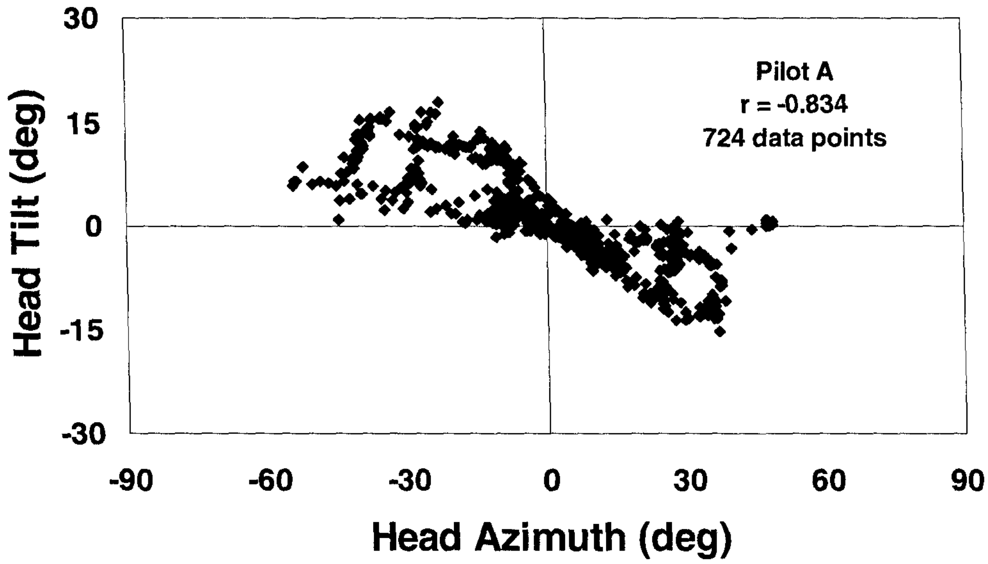



Figure 12. Scattergram of the 742 observations of head tilt against head azimuth, both in degrees, for the first of Pilot A's slaloms. The correlation coefficient is -0.834.

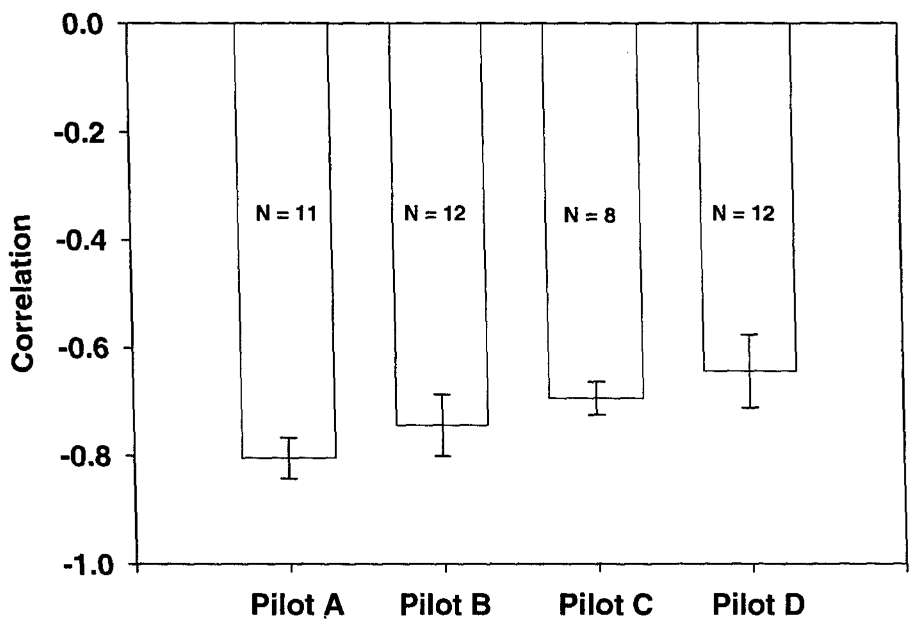



Figure 13. Correlation coefficients between head tilt and azimuth averaged across all flights for each pilot. The error bars are 95% confidence intervals.

The correlations and scattergrams of Figures 4 through 7 provide a ready method for quantifying the relation between head azimuth and tilt; however, they collapse data across all the slaloms for each of the pilots. The scattergram of head tilt against azimuth recorded during the Pilot A's first flight is shown in Figure 12. For this flight the

correlation between these two variables is -0.834. Since Pilot A flew the slalom 11 times, there are 11 such correlations, one for each flight. The average of these 11 correlations is -0.8051, with a standard deviation of 0.0378. These are shown as the leftmost bar of the histogram in Figure 13. This histogram shows the average correlations (with 95% confidence intervals) across the slalom maneuvers for each of the pilots as identified on the abscissa. The number of slalom flights for each pilot is identified in its respective bar. Figure 13 confirms the consistency across all pilots of the substantial negative correlation between head tilt and head azimuth. That the correlation is negative derives from the sign convention; left head turns and head tilts are negative while right head turns and head tilts are positive. The negative correlations mean that, during the slalom, when pilots turn their heads to the left, they tilt their heads to the right, and when they turn their heads to the right, they tilt their heads to the left. Furthermore, since the values of these correlations are relatively large (the average R-square across the four pilots is 0.5247), the relationship between head tilt and azimuth is proportionately quite strong; that is, the more the head turns in one direction, the more it tilts in the other.

The relationship between head pitch and head azimuth

Pilot A's head azimuth and head pitch recorded during the first execution of the slalom are plotted in Figure 14. Azimuth is plotted in Figure 14 exactly as plotted in Figure 3. Head pitch, shown as the dotted line, is referenced to the right ordinate of Figure 14, also in degrees. Positive degrees of head pitch indicate that the chin was pitched upward while negative degrees indicate that the chin was pitched downward with respect to the straight ahead zero calibration. As in Figure 3, the abscissa is the number of data points. As described above, the aircraft turns that were required to successfully execute the slalom are reflected in the head azimuth data, the two successive turns to the left followed by the two successive turns to the right.

During Pilot A's first slalom, head pitch ranged from a high of about -16° to a low of about -28°. In other words, throughout the slalom, Pilot A's head was pitched down relative to the zero head pitch calibration. Appendix A is a catalogue of the head position data recorded during each of the Pilot A's slaloms. With the exception of flights 8 through 11, Pilot A's head pitch was consistently downward relative to the calibrated zero, throughout each slalom. Pilot A was not the only pilot whose head assumed this pitch down posture. Appendices B through D catalogue head pitch data for every slalom of pilots B through D, respectively. As is evident in these Appendices, these three pilots also consistently assumed a head pitch down posture throughout for every one of their slaloms. As mentioned earlier, the focus of the present paper is to describe the correlations among head azimuth, pitch, and tilt and not describe the characteristics of these individual parameters per se since such descriptions have been reported previously (Rostad et al., 2001, 2003; Rostad, Rash, and Crowley, 2003; Stelle et al., 2003a, b).

A comparison of Figures 3 to 14 suggests that at least three factors make the relationship between head azimuth and head pitch less clear and more complicated than the relationship between head azimuth and head tilt. The first factor is the amount of consistency in the relationship between head azimuth and head pitch. The first sustained

turn of the head to the left, evident by data point 30, is clearly associated with an upward pitch of the head. At this point, the head has turned about 40° to the left and is pitched up by about 6°; that is, from about -22° to a high of about -16°. With the return of the head to the forward posture, the head pitch returns to about -22°. It is important to note, however, that there is little convincing evidence of a head pitch occurring during the second sustained turn of the head to the left, which is evident at about data point number 260, or at about 26 seconds into the slalom. This shows that head turns can occur without any clear evidence of an associated change in head pitch. Figure 14 shows that the second head turn to the left was followed by two successive right head turns to the right. The first of these right head turns is clearly evident with data point number about 450, or at about 45 seconds into the slalom, and the second right head turn is evident with data point about 650, or at about 65 seconds into the turn. Both of these right head turns are clearly associated with the head pitching upward to about -16°. Inspection of the Appendices show that there is a strong propensity for the head to pitch up as the head turns, but as illustrated in Figure 14, there are head turns that do occur without clear evidence of changes in head pitch.

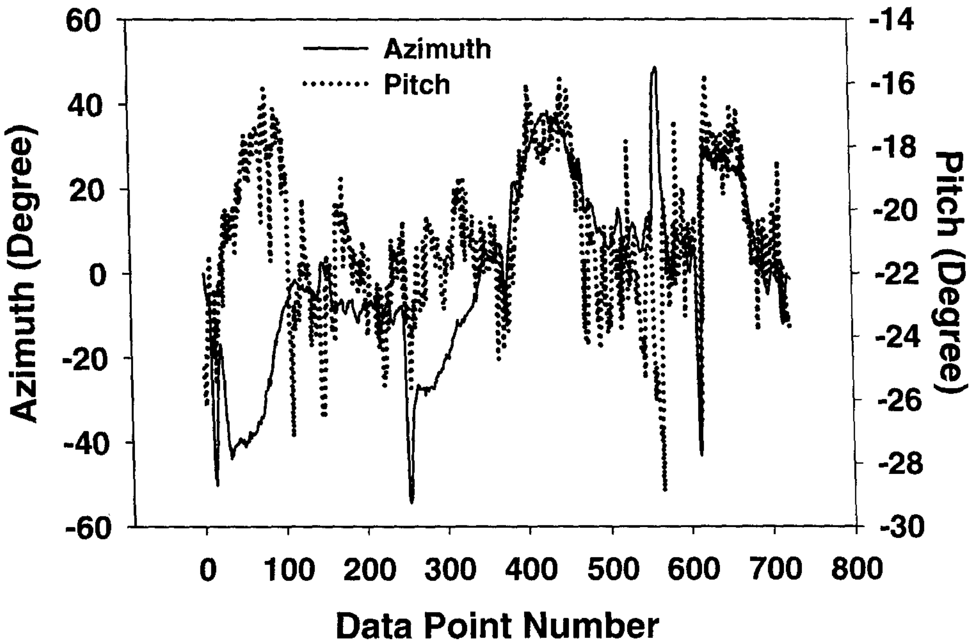



Figure 14. Head azimuth on the left ordinate and head pitch on the right ordinate, both in degrees, as a function of time (10 datapoints = 1 second) for Pilot A's first slalom.

A second factor that complicates the relationship between head azimuth and pitch is the presence of what appears to be relatively substantial amounts of high frequency variability in head pitch. This relatively high frequency variability appears as a component of head pitch behavior superimposed on the lower frequency head pitch associated with changes in head azimuth. A spectral decomposition analysis and comparison of head pitch behavior would evaluate this impression, but such an analysis is beyond the scope of the present paper.

## Table 1.

Correlation between head azimuth and head tilt for each slalom of each pilot calculated for: (a) the whole slalom, (b) when the head was turned left more than 10°, (c) when the head was within 10° of the center, and (d) when the head was turned to the right more than 10°. The number of observations is shown for each of these correlations.

| | Whole Slalom | | Azimuth < -10° | | Azimuth between +/- 10° | | Azimuth > 10° | |
|---|---|---|---|---|---|---|---|---|
| Flight | N | Correlation | N | Correlation | N | Correlation | N | Correlation |
| Pilot A | | | | | | | | |
| 75 | 724 | 0.2507 | 194 | 0.0142 | 319 | -0.0129 | 211 | 0.2532 |
| 76 | 690 | 0.0409 | 149 | -0.2844 | 321 | -0.1799 | 220 | 0.0492 |
| 77 | 798 | 0.3024 | 162 | 0.1082 | 370 | 0.0598 | 266 | 0.1563 |
| 81 | 420 | -0.3666 | 177 | -0.6889 | 61 | -0.2725 | 182 | 0.5209 |
| 82 | 426 | -0.2829 | 158 | -0.2887 | 98 | -0.0594 | 170 | 0.4052 |
| 83 | 460 | -0.2924 | 158 | -0.4528 | 128 | 0.0256 | 174 | 0.5349 |
| 84 | 450 | -0.4853 | 146 | -0.5476 | 111 | -0.3090 | 193 | 0.4082 |
| 92 | 444 | -0.2007 | 153 | -0.3640 | 158 | -0.2009 | 133 | 0.4098 |
| 93 | 436 | -0.2565 | 146 | -0.5723 | 131 | -0.3136 | 159 | 0.8146 |
| 94 | 480 | -0.1588 | 124 | -0.5249 | 181 | -0.2431 | 175 | 0.6701 |
| 95 | 492 | -0.0852 | 104 | -0.0860 | 216 | -0.1409 | 172 | 0.5202 |
| | Mean | -0.1395 | | -0.3352 | | -0.1497 | | 0.4311 |
| | SD | 0.2482 | | 0.2574 | | 0.1346 | | 0.2204 |
| Pilot B | | | | | | | | |
| 47 | 748 | 0.4356 | 162 | 0.2426 | 172 | -0.1025 | 414 | 0.6225 |
| 48 | 757 | 0.5825 | 159 | 0.0764 | 193 | 0.0981 | 405 | 0.6777 |
| 49 | 788 | 0.3718 | 193 | 0.2626 | 178 | -0.2015 | 417 | 0.5369 |
| 50 | 732 | 0.1493 | 172 | 0.3431 | 186 | 0.0158 | 374 | 0.2553 |
| 54 | 446 | 0.3572 | 83 | -0.3357 | 109 | 0.0894 | 254 | 0.5062 |
| 55 | 476 | 0.3573 | 92 | -0.6041 | 119 | 0.3412 | 265 | 0.4925 |
| 56 | 465 | 0.3424 | 86 | -0.1639 | 90 | 0.1360 | 289 | 0.2571 |
| 57 | 490 | 0.3959 | 81 | -0.2028 | 69 | -0.1712 | 340 | 0.7574 |
| 64 | 506 | 0.2925 | 126 | -0.1309 | 113 | -0.0038 | 267 | 0.4386 |
| 65 | 468 | 0.5046 | 86 | -0.5176 | 138 | 0.5357 | 244 | 0.7461 |
| 66 | 467 | 0.4410 | 96 | -0.1880 | 136 | 0.3507 | 235 | 0.5672 |
| 67 | 434 | 0.1667 | 78 | -0.0645 | 119 | 0.4484 | 237 | 0.4145 |
| | Mean | 0.3664 | | -0.1069 | | 0.1280 | | 0.5227 |
| | SD | 0.1244 | | 0.2992 | | 0.2426 | | 0.1660 |
| Pilot C | | | | | | | | |
| 147 | 684 | 0.5000 | 138 | 0.4120 | 281 | -0.1049 | 265 | 0.4324 |
| 148 | 651 | 0.5901 | 200 | 0.0330 | 177 | 0.1744 | 274 | 0.3901 |
| 149 | 717 | 0.5015 | 178 | 0.0097 | 237 | 0.4017 | 302 | 0.3322 |
| 150 | 739 | 0.5374 | 184 | -0.1052 | 212 | 0.2552 | 343 | 0.4347 |
| 151 | 470 | 0.6016 | 135 | 0.0599 | 123 | 0.3619 | 212 | 0.4581 |
| 152 | 522 | 0.4875 | 125 | 0.2662 | 129 | 0.0457 | 268 | 0.2203 |
| 153 | 517 | 0.4332 | 124 | 0.3025 | 178 | 0.2365 | 215 | 0.3223 |
| 154 | 504 | 0.3851 | 105 | -0.0405 | 161 | 0.3621 | 238 | 0.4089 |
| | Mean | 0.5045 | | 0.1172 | | 0.2166 | | 0.3749 |
| | SD | 0.0732 | | 0.1851 | | 0.1744 | | 0.0790 |
| Pilot D | | | | | | | | |
| 116 | 769 | 0.5196 | 323 | 0.1621 | 202 | 0.0328 | 244 | 0.3592 |
| 117 | 757 | 0.0886 | 197 | -0.3049 | 318 | -0.1392 | 242 | 0.1273 |
| 118 | 769 | 0.2488 | 224 | 0.0928 | 289 | -0.2415 | 256 | 0.0337 |
| 119 | 760 | 0.3323 | 187 | 0.0885 | 334 | -0.1381 | 239 | -0.1555 |
| 128 | 452 | 0.5444 | 108 | 0.1468 | 161 | -0.4843 | 183 | 0.5492 |
| 129 | 481 | 0.1792 | 128 | -0.3364 | 135 | 0.1679 | 218 | 0.2064 |
| 130 | 486 | 0.1072 | 123 | -0.0729 | 155 | -0.1243 | 208 | -0.1980 |
| 132 | 456 | 0.4440 | 107 | -0.4928 | 161 | 0.2877 | 188 | 0.1954 |
| 133 | 498 | 0.3531 | 135 | -0.2649 | 160 | 0.0861 | 203 | 0.1701 |
| 134 | 511 | 0.3674 | 118 | 0.1125 | 202 | 0.2148 | 191 | 0.0221 |
| 135 | 529 | 0.2045 | 122 | 0.1142 | 188 | -0.0443 | 219 | -0.0032 |
| | Mean | 0.3081 | | -0.0686 | | -0.0348 | | 0.1188 |
| | SD | 0.1564 | | 0.2372 | | 0.2238 | | 0.2160 |

A third factor, also evident in Figure 14, that complicates the relationship between head azimuth and head pitch is the observation that the head apparently tends to pitch upward when the head turns either to the right or to the left. This would imply that, based on the sign conventions, the correlation between head azimuth and head pitch would be negative when the head is turned to the left but positive when the head is turned to the right. This suggests that the correlation between head azimuth and head pitch calculated over the full range of head azimuth could be very misleading. Consequently, the analysis of the relationship between head azimuth and pitch should differentiate left from right head azimuth.

Such an analysis for each flight for each pilot individually is summarized in Table 1. The first column identifies the flight number, while the second column is the number of data points recorded over the whole flight. The third column is the correlation between head azimuth and head pitch calculated over the whole flight. The fourth column is the number of data points recorded when the head was turned to the left by more than 10°, while the fifth column is the correlation between head azimuth and head pitch calculated with this subset of the data. The sixth column is the number of data points recorded when the head was between ±10° of the calibrated straight ahead zero, while the seventh column is the correlation between head azimuth and head pitch calculated with this subset of the data. The eighth column is the number of data points recorded when the head was turned to the right by more than 10°, while the ninth column is the correlation between head azimuth and head pitch calculated with this subset of the data.

For example, the first flight tabulated is number 75, flown by Pilot A. The total number of data points recorded during this flight was 724. The correlation between head azimuth and head pitch over the whole flight was 0.251. The correlation was recalculated when the head was turned to the left by more than 10°; that is, when the azimuth was less than -10°. Of the total 724 data points of the flight, 194 of them were recorded when the head was turned more than 10° to the left; that is, when the azimuth was less than -10°. The correlation between head azimuth and head pitch calculated on the subset of the dataset was 0.014. Similarly, the correlation calculated when the head was between 10° to the left and 10° to the right of the straight ahead zero calibration was -0.0129. Of the 724 data points recorded during the flight, 319 were recorded when the head was ±10° of the calibrated straight ahead zero. Finally, the correlation between head azimuth and head tilt was calculated for the data recorded when the head was turned to the right by more than 10°. The correlation was 0.253, calculated on 211 of the 724 data points.

Figures 15 through 18 help to visualize and interpret these correlations of head azimuth to head pitch calculated for each flight individually for Pilots A through D, respectively. The correlations are organized in groups of four bars each, with each group of four referring to the flight identified on the abscissa in a fashion exactly analogous to the way Table 1 referred to each flight. The first bar of each group shows the correlation between head azimuth and head pitch calculated over the whole flight. The second bar of each group shows the correlation calculated with the head at least 10° to the left. The

third bar shows the correlation calculated when the head was between $\pm 10°$. The fourth bar shows the correlation calculated when the head was turned to the right by at least 10°.

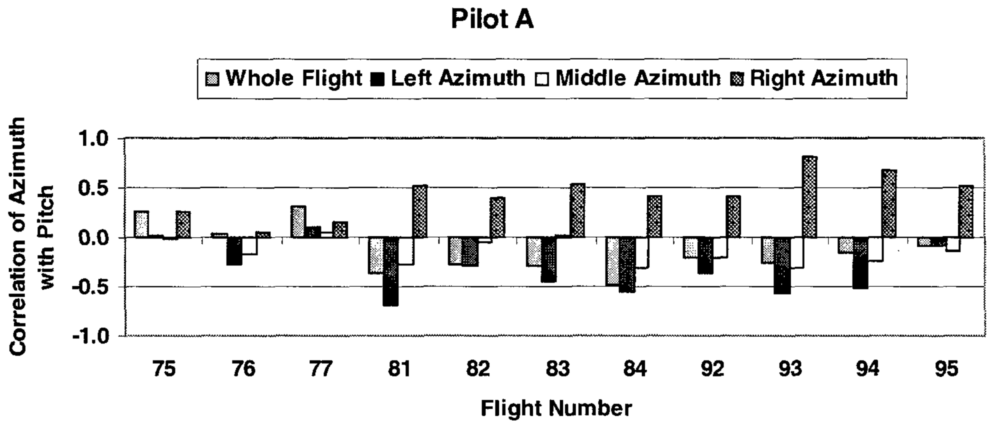



Figure 15. Correlation of head azimuth with head pitch for each of Pilot A's 11 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within $\pm$ 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

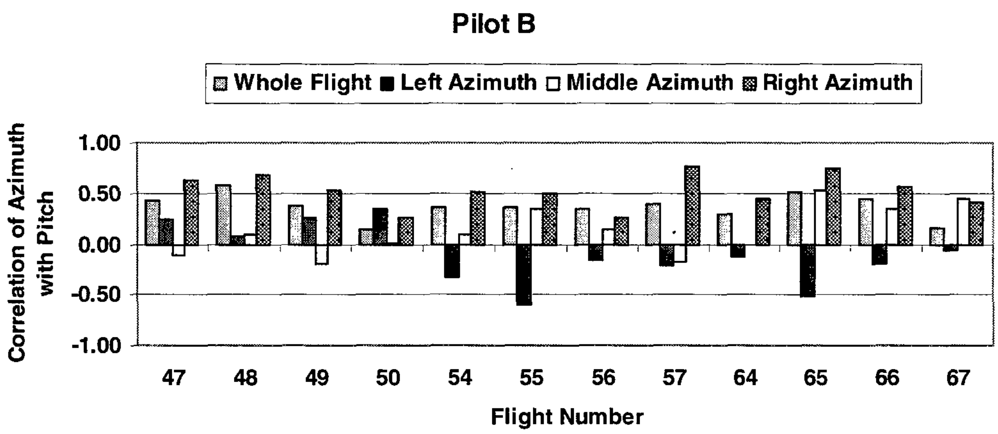



Figure 16. Correlation of head azimuth with head pitch for each of Pilot B's 12 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within $\pm$ 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

## Pilot C

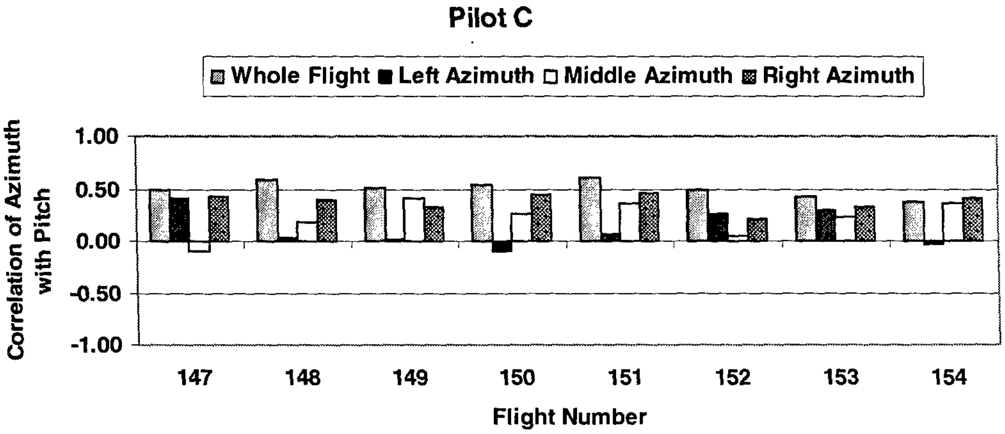



Figure 17. Correlation of head azimuth with head pitch for each of Pilot C's 8 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

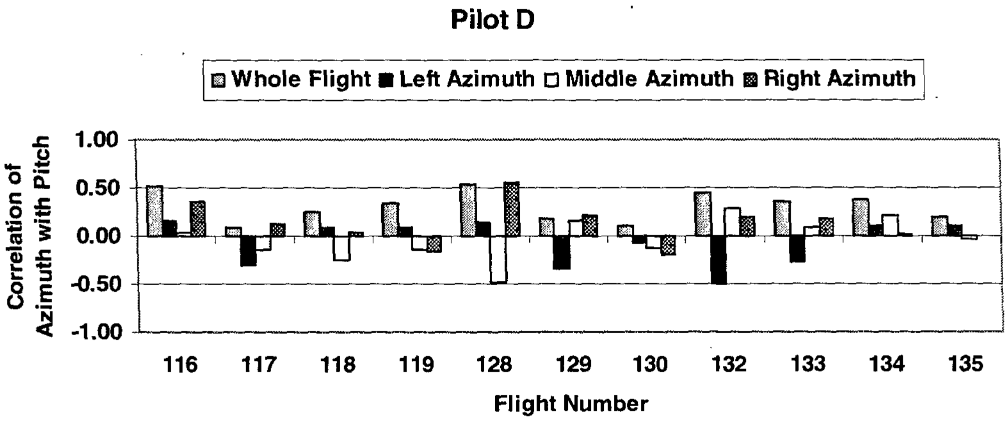



Figure 18. Correlation of head azimuth with head pitch for each of Pilot D's 11 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

Figure 15, which contains the correlations calculated for Pilot A's flights, shows that for flights 81 through 95, when the head is turned to the right, the head azimuth and pitch are positively correlated. Conversely, when the head is turned to the left, head azimuth and pitch are negatively correlated, except for flights 75 and 77. This indicates that Pilot A had a tendency to look in an upward direction when the head was turned to the right by more than 10° or when it was turned to the left by more than 10°. This relationship is not reflected in the correlations when they are calculated over the whole flight. The correlations calculated for the middle 20° of head position are all smaller than the comparable correlations calculated when the head is turned either to the left or to the right for the same flight. Consequently, there was less of a relationship between head azimuth and pitch when Pilot A's head was within ±10° of center.

The correlations calculated for Pilot B are illustrated in Figure 16. The pattern among these correlations differs markedly from those of Pilot A. Almost all of Pilot B's correlations are positive. For example, the correlation between head azimuth and pitch calculated with the 748 data points that comprise the whole of Pilot B's first flight, Flight 47, was 0.4356. This indicates that when Pilot B turned to the right, the head pitched up; whereas when it turned to the left, it pitched down. For most of Pilot B's flights, the correlation between azimuth and pitch is strongest when the head is oriented to the right; again suggesting that the Pilot B's head pitched up when turned to the right. In some flights, for example, 54, 55, and 65, the correlation between head azimuth and elevation was negative when turned to the left, indicating that during these flights, the head tended to pitch up when turned to the left.

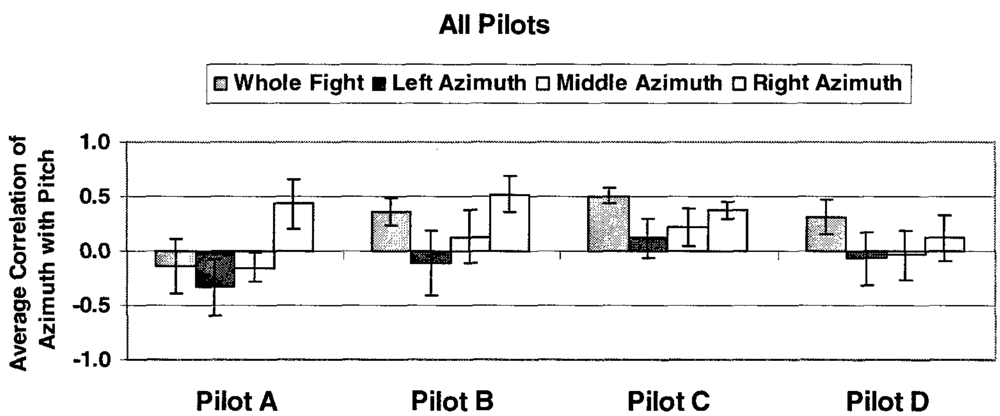



Figure 19. Correlation coefficients between head azimuth and head pitch averaged across all flights for each of the four pilots. Four averages are shown for each pilot: The left bar of each group is the average correlation calculated over the whole flight; the second bar of each group is the average correlation calculated when the head was turned more than 10° to the left; the third bar is the average correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the average correlation calculated when the head was turned more than 10° to the right. The error bars show ± 1.0 S.D.

The correlations calculated for Pilots C and D are illustrated in Figures 17 and 18, respectively. The pattern of correlations between head azimuth and head pitch apparently differ markedly from one flight to another for the same pilot and between pilots. The magnitude of these within and between pilot differences is illustrated in Figure 19, which demonstrates that segmenting the flights into left, middle and right azimuth has different effects on these correlations for the four different pilots. Furthermore, the size of the error bars for each histogram reflects the large variability within each pilot's data, a variability that can be substantial. Clearly, there is substantial within subject and between subject variability in the strength of the correlation between head azimuth and head pitch. In other words, for a segment of one execution of the slalom, the correlation between head azimuth and head pitch can be substantial; but for another slalom by the same pilot, or even another segment of the same slalom, the correlations can be negligible or even of an opposite sign.

## The relationship between head pitch and head tilt

The variability in the head pitch data and the lack of consistency in the correlation between head azimuth and head pitch do not eliminate the possibility that head pitch is also an important determinant of head tilt. The existence of a relationship between the two is strongly suggested by Figure 20, which plots head pitch and head tilt recorded during Pilot A's first slalom. Head pitch is plotted in degrees as the solid line referenced to the left ordinate, and head tilt is plotted in degrees as the dotted line referenced to the right ordinate. Both head pitch and tilt are shown as a function of data point number on the abscissa. This is only one flight; Appendix A catalogues the head tracking data recorded for each of Pilot A's 11 slalom flights, in the format of Figure 20. Appendix B presents the head pitch and head tilt data obtained during Pilot B's 12 slalom flights, Appendix C presents the head pitch and head tilt data obtained during Pilot C's 8 slaloms, and Appendix D presents the head pitch and head tilt data obtained during Pilot D's 11 slaloms.

The two left turns and the two right turns needed to execute the slalom is evident in the pattern of head pitch and tilt movements recorded in Figure 20, and in most of the comparable figures in the Appendices. The correlations between head pitch and tilt are explored quantitatively in Table 2 for each flight for each pilot in exactly the same format as Table 1. Like Table 1, Table 2 contains nine columns for each of the pilots. The first column identifies the flight number, and the second column is the number of data points recorded over the whole flight. The third column is the correlation between head pitch and head tilt calculated over the whole flight. The fourth column is the number of data points recorded with the azimuth left by more than 10°, and the fifth column is the correlation between head pitch and tilt calculated with this subset of the data. The sixth column is the number of data points recorded with the azimuth between $\pm$10° of the calibrated straight ahead zero, and the seventh column is the correlation between head pitch and head tilt calculated with this subset of the data. The eighth column is the number of data points recorded with the azimuth right by more than 10°, and the ninth

column is the correlation between head pitch and tilt calculated with this subset of the data.

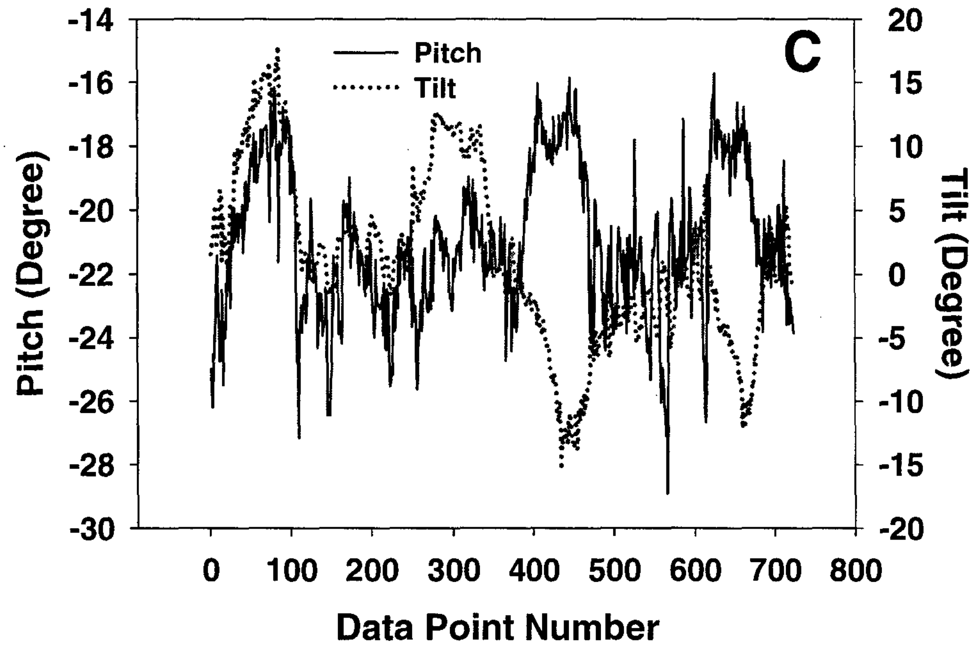



Figure 20. Head pitch on the left ordinate and head tilt on the right ordinate, both in degrees, as a function of time (10 datapoints = 1 second) for Pilot A's first slalom.

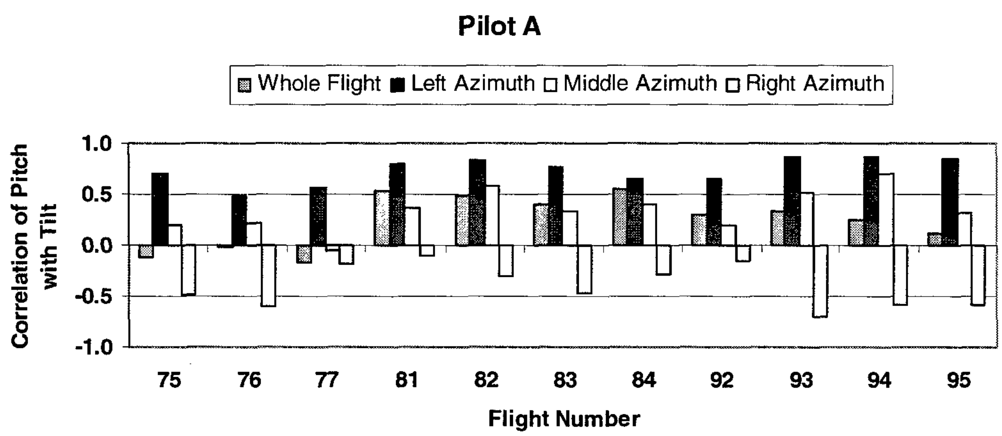



Figure 21. Correlation of head pitch with head tilt for each of Pilot A's 11 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

Table 2.

Correlation between head pitch and head tilt for each slalom of each pilot calculated for: (a) the whole slalom, (b) when the head was turned left more than 10°, (c) when the head was within 10° of the center, and (d) when the head was turned to the right more than 10°. The number of observations is shown for each of these correlations.

| | Whole Slalom | | Azimuth < -10° | | Azimuth between +/- 10° | | Azimuth > 10° | |
|---|---|---|---|---|---|---|---|---|
| Flight | N | Correlation | N | Correlation | N | Correlation | N | Correlation |
| Pilot A | | | | | | | | |
| 75 | 724 | -0.116 | 194 | 0.695 | 319 | 0.207 | 211 | -0.480 |
| 76 | 690 | -0.015 | 149 | 0.482 | 321 | 0.225 | 220 | -0.601 |
| 77 | 798 | -0.161 | 162 | 0.574 | 370 | -0.057 | 266 | -0.190 |
| 81 | 420 | 0.532 | 177 | 0.800 | 61 | 0.375 | 182 | -0.105 |
| 82 | 426 | 0.484 | 158 | 0.834 | 98 | 0.588 | 170 | -0.304 |
| 83 | 460 | 0.395 | 158 | 0.774 | 128 | 0.329 | 174 | -0.461 |
| 84 | 450 | 0.556 | 146 | 0.657 | 111 | 0.396 | 193 | -0.276 |
| 92 | 444 | 0.292 | 153 | 0.654 | 158 | 0.201 | 133 | -0.143 |
| 93 | 436 | 0.334 | 146 | 0.862 | 131 | 0.517 | 159 | -0.699 |
| 94 | 480 | 0.247 | 124 | 0.875 | 181 | 0.697 | 175 | -0.584 |
| 95 | 492 | 0.114 | 104 | 0.853 | 216 | 0.312 | 172 | -0.585 |
| | Mean | 0.242 | | 0.733 | | 0.345 | | -0.403 |
| | SD | 0.255 | | 0.130 | | 0.208 | | 0.207 |
| Pilot B | | | | | | | | |
| 47 | 748 | -0.314 | 162 | 0.577 | 172 | 0.109 | 414 | -0.389 |
| 48 | 757 | -0.398 | 159 | 0.538 | 193 | 0.505 | 405 | -0.465 |
| 49 | 788 | -0.274 | 193 | 0.301 | 178 | 0.241 | 417 | -0.363 |
| 50 | 732 | 0.088 | 172 | 0.758 | 186 | 0.536 | 374 | -0.123 |
| 54 | 446 | -0.276 | 83 | 0.598 | 109 | 0.073 | 254 | -0.474 |
| 55 | 476 | -0.286 | 92 | 0.593 | 119 | -0.026 | 265 | -0.493 |
| 56 | 465 | -0.330 | 86 | 0.637 | 90 | 0.112 | 289 | -0.426 |
| 57 | 490 | -0.302 | 81 | 0.682 | 69 | 0.138 | 340 | -0.701 |
| 64 | 506 | -0.151 | 126 | 0.560 | 113 | -0.059 | 267 | -0.149 |
| 65 | 468 | -0.494 | 86 | 0.041 | 138 | -0.333 | 244 | -0.603 |
| 66 | 467 | -0.401 | 96 | 0.559 | 136 | -0.108 | 235 | -0.612 |
| 67 | 434 | -0.236 | 78 | 0.479 | 119 | 0.043 | 237 | -0.657 |
| | Mean | -0.281 | | 0.527 | | 0.103 | | -0.455 |
| | SD | 0.145 | | 0.189 | | 0.243 | | 0.183 |
| Pilot C | | | | | | | | |
| 147 | 684 | -0.486 | 138 | 0.016 | 281 | 0.021 | 265 | -0.583 |
| 148 | 651 | -0.592 | 200 | -0.093 | 177 | -0.174 | 274 | -0.495 |
| 149 | 717 | -0.390 | 178 | 0.507 | 237 | -0.308 | 302 | -0.399 |
| 150 | 739 | -0.425 | 184 | 0.246 | 212 | -0.063 | 343 | -0.208 |
| 151 | 470 | -0.471 | 135 | 0.381 | 123 | -0.305 | 212 | -0.354 |
| 152 | 522 | -0.451 | 125 | 0.089 | 129 | 0.304 | 268 | -0.484 |
| 153 | 517 | -0.350 | 124 | 0.515 | 178 | 0.237 | 215 | -0.657 |
| 154 | 504 | -0.245 | 105 | 0.630 | 161 | -0.566 | 238 | -0.314 |
| | Mean | -0.426 | | 0.286 | | -0.107 | | -0.437 |
| | SD | 0.103 | | 0.263 | | 0.293 | | 0.147 |
| Pilot D | | | | | | | | |
| 116 | 769 | -0.270 | 323 | 0.103 | 202 | -0.083 | 244 | 0.080 |
| 117 | 757 | -0.117 | 197 | 0.367 | 318 | -0.222 | 242 | -0.160 |
| 118 | 769 | -0.189 | 224 | 0.158 | 289 | 0.037 | 256 | -0.063 |
| 119 | 760 | -0.205 | 187 | 0.225 | 334 | 0.148 | 239 | -0.378 |
| 128 | 452 | -0.025 | 108 | 0.206 | 161 | 0.571 | 183 | 0.306 |
| 129 | 481 | -0.129 | 128 | 0.521 | 135 | -0.174 | 218 | -0.172 |
| 130 | 486 | -0.096 | 123 | 0.518 | 155 | -0.151 | 208 | -0.101 |
| 132 | 456 | 0.663 | 107 | 0.080 | 161 | -0.175 | 188 | -0.050 |
| 133 | 498 | -0.350 | 135 | 0.267 | 160 | 0.142 | 203 | -0.202 |
| 134 | 511 | -0.243 | 118 | 0.350 | 202 | -0.173 | 191 | -0.091 |
| 135 | 529 | 0.204 | 122 | 0.521 | 188 | -0.439 | 219 | -0.568 |
| | Mean | -0.069 | | 0.301 | | -0.047 | | -0.127 |
| | SD | 0.283 | | 0.166 | | 0.266 | | 0.226 |

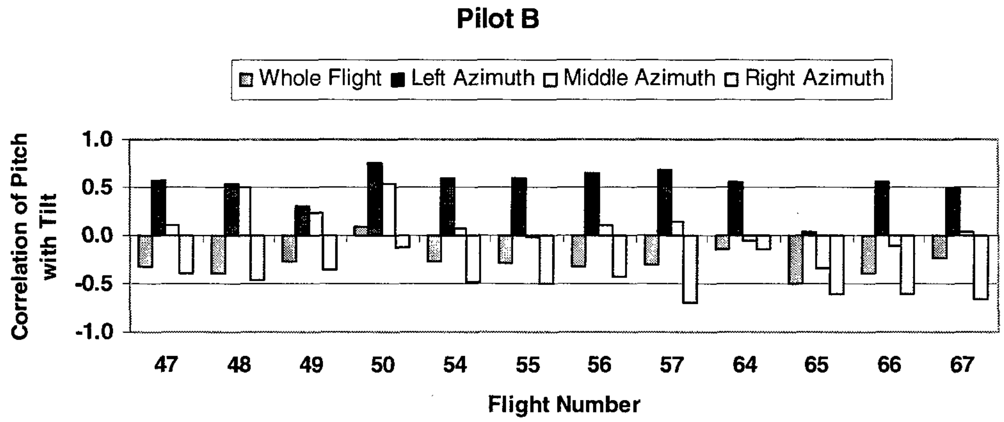



Figure 22. Correlation of head pitch with head tilt for each of Pilot B's 12 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

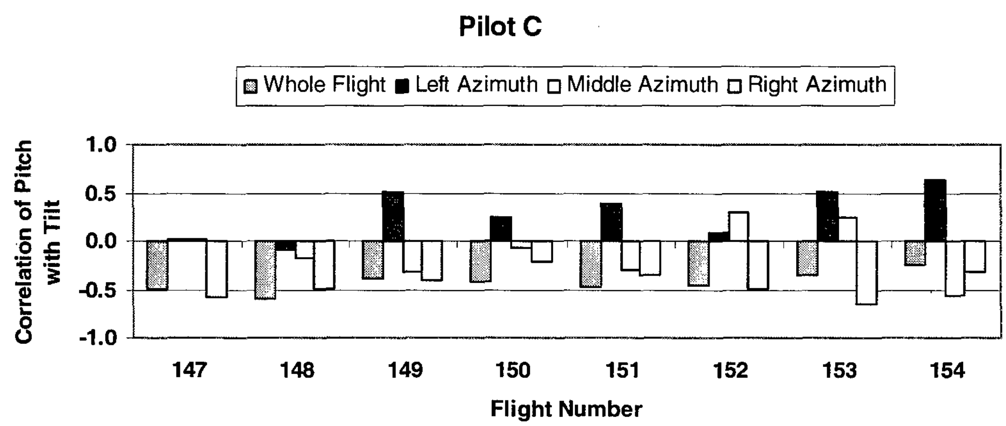



Figure 23. Correlation of head pitch with head tilt for each of Pilot C's 8 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

Figures 21, 22, 23, and 24 display these correlations for each flight of Pilot A through D, respectively. A consistent pattern emerges from these figures. The correlation between head pitch and tilt is consistently positive when the head is turned to

the left by more than 10°. This is true for every flight of Pilots A, B, and D, and all but flight 148 of Pilot C. In other words, when the head is oriented to the left by more than 10°, as the head pitches upward, it tilts toward the right, and as the head pitches downward, it tilts toward the left. These relationships are the ones dictated by the sign conventions since pitch motion upward and tilt motion rightward are in the positive direction; whereas, pitch motion downward and tilt motion leftward are in the negative direction. However, since, as discussed earlier in the section describing the correlation between head azimuth and head tilt, the head rarely tilts to the left when it is turned to the left, it is more accurate to say that as the head pitches upward, the head tilts rightward from vertical, and as the head returns from the upward pitch, the head returns from its rightward tilt toward the vertical in a leftward motion. The returning downward motion of the pitch and the returning leftward motion of the tilt contribute to the positive correlation.

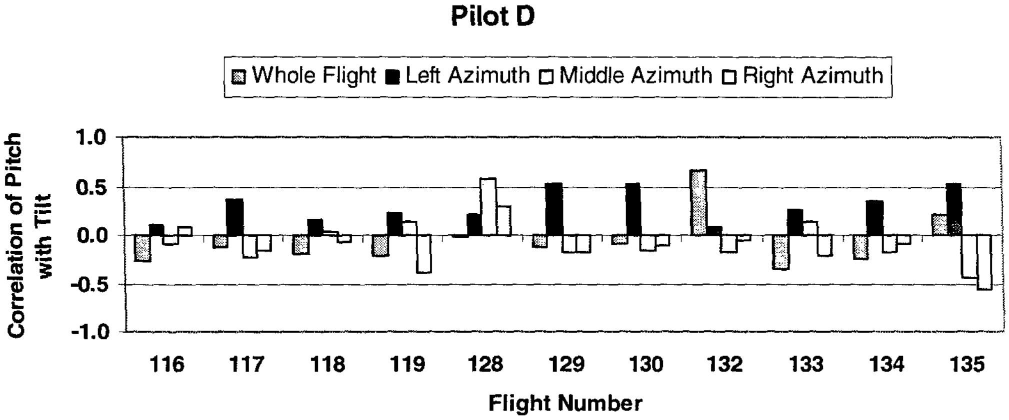



Figure 24. Correlation of head pitch with head tilt for each of Pilot D's 11 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within $\pm$ 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

The same logic applies when the head is turned to the right by more than 10° as shown in Table 2 and Figures 21 through 24; the correlation between head pitch and head tilt is consistently negative when the head is turned to the right by more than 10°. This is true for every flight of Pilots A, B, and C, and all the flights of Pilot D except 116 and 128. In other words, when the head is oriented to the right by more than 10°, as the head pitches upward, it tilts toward the left, and as the head pitches downward, it tilts toward the right. These relationships, too, result from the sign conventions since pitch motion upward and tilt motion rightward are in the positive direction; whereas, pitch motion downward and tilt motion leftward are in the negative direction. Furthermore, as discussed earlier in the section describing the correlation between head azimuth and head tilt, the head rarely tilts to the right when it is turned to the right. It is more accurate to say that as the head pitches upward, the head tilts leftward from vertical, and as the head returns from the upward pitch, the head returns from its leftward tilt toward the vertical in

a rightward motion. The returning downward motion of the pitch and the returning rightward motion of the tilt contribute to the negative correlation.

The consistency of these correlations is evident in Figure 25, which plots for each of the pilots these correlations averaged over their respective flights. Error bars are the standard deviations. The correlations calculated over the whole flights and when the head was between ± 10° show little regularity within and between pilots; but the consistency of the positive correlations when the heads are turned left by more than 10° and the consistency of the negative correlations when the heads are turned right by more than 10° is evident for the four pilots.

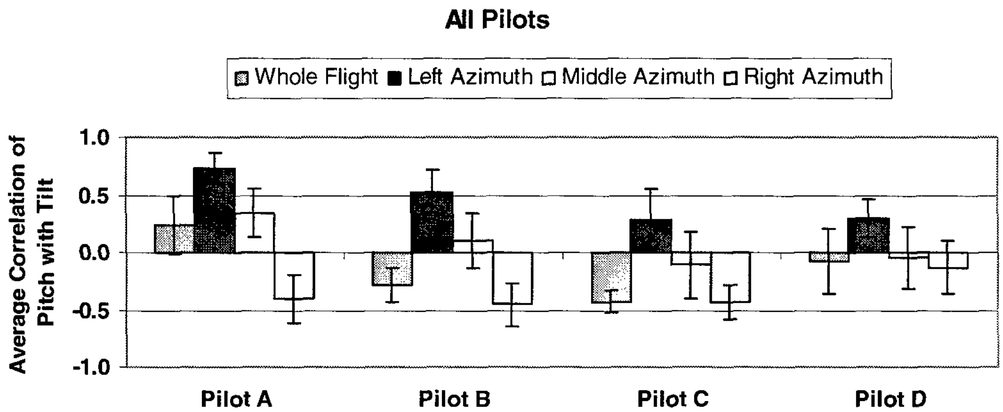



Figure 25. Correlation coefficients between head pitch and head tilt averaged across all flights for each of the four pilots. Four averages are shown for each pilot: The left bar of each group is the average correlation calculated over the whole flight; the second bar of each group is the average correlation calculated when the head was turned more than 10° to the left; the third bar is the average correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the average correlation calculated when the head was turned more than 10° to the right. The error bars show ± 1.0 S.D.

A precaution needs to be taken in the interpretation of these correlations since a variable and idiosyncratic correlation between head pitch and head azimuth has been identified, as well as a strong, reliable correlation between head tilt and head azimuth. The variable and idiosyncratic correlation between head pitch and head azimuth raises the possibility that the correlation between head azimuth and head pitch could have implications for the interpretation of the correlation between head pitch and tilt. It is possible, for example, that those instances when head azimuth and head pitch are strongly correlated could have inflated the observed correlation between head pitch and head tilt. Such an inflation of the correlation could occur in those instances because the correlation of head tilt and pitch could indirectly include the strong correlation of head azimuth with head tilt mediated by the occasionally substantial correlation of head azimuth with head pitch. In order to control for this possibility, partial correlations were calculated.

Table 3.

Partial correlation between head pitch and head tilt with head azimuth influence controlled for each slalom of each pilot calculated for: (a) the whole slalom, (b) when the head was turned left more than 10°, (c) when the head was within 10° of the center, and (d) when the head was turned to the right more than 10°. The number of observations is shown for each of these correlations.

| | Whole Slalom | | Azimuth < -10° | | Azimuth between +/- 10° | | Azimuth > 10° | |
|---|---|---|---|---|---|---|---|---|
| Flight | N | Correlation | N | Correlation | N | Correlation | N | Correlation |
| Pilot A | | | | | | | | |
| 75 | 724 | 0.175 | 194 | 0.713 | 319 | 0.289 | 211 | -0.480 |
| 76 | 690 | 0.042 | 149 | 0.482 | 321 | 0.140 | 220 | -0.601 |
| 77 | 798 | 0.160 | 162 | 0.580 | 370 | -0.021 | 266 | -0.190 |
| 81 | 420 | 0.444 | 177 | 0.753 | 61 | 0.281 | 182 | -0.105 |
| 82 | 426 | 0.467 | 158 | 0.834 | 98 | 0.650 | 170 | -0.304 |
| 83 | 460 | 0.280 | 158 | 0.812 | 128 | 0.395 | 174 | -0.461 |
| 84 | 450 | 0.331 | 146 | 0.730 | 111 | 0.317 | 193 | -0.276 |
| 92 | 444 | 0.219 | 153 | 0.732 | 158 | 0.102 | 133 | -0.143 |
| 93 | 436 | 0.240 | 146 | 0.910 | 131 | 0.436 | 159 | -0.699 |
| 94 | 480 | 0.199 | 124 | 0.946 | 181 | 0.673 | 175 | -0.584 |
| 95 | 492 | 0.076 | 104 | 0.897 | 216 | 0.282 | 172 | -0.585 |
| | Mean | 0.239 | | 0.763 | | 0.322 | | -0.403 |
| | SD | 0.135 | | 0.141 | | 0.213 | | 0.207 |
| Pilot B | | | | | | | | |
| 47 | 748 | 0.095 | 162 | 0.569 | 172 | 0.092 | 414 | 0.010 |
| 48 | 757 | 0.093 | 159 | 0.534 | 193 | 0.551 | 405 | -0.228 |
| 49 | 788 | -0.035 | 193 | 0.275 | 178 | 0.227 | 417 | -0.230 |
| 50 | 732 | 0.286 | 172 | 0.729 | 186 | 0.592 | 374 | -0.079 |
| 54 | 446 | -0.034 | 83 | 0.730 | 109 | 0.088 | 254 | -0.386 |
| 55 | 476 | -0.040 | 92 | 0.669 | 119 | 0.118 | 265 | -0.373 |
| 56 | 465 | -0.146 | 86 | 0.692 | 90 | 0.137 | 289 | -0.398 |
| 57 | 490 | -0.006 | 81 | 0.778 | 69 | 0.120 | 340 | -0.513 |
| 64 | 506 | 0.116 | 126 | 0.581 | 113 | -0.063 | 267 | 0.022 |
| 65 | 468 | -0.139 | 86 | 0.109 | 138 | -0.180 | 244 | -0.315 |
| 66 | 467 | -0.138 | 96 | 0.595 | 136 | -0.016 | 235 | -0.549 |
| 67 | 434 | -0.171 | 78 | 0.483 | 119 | 0.235 | 237 | -0.617 |
| | Mean | -0.010 | | 0.562 | | 0.158 | | -0.305 |
| | SD | 0.136 | | 0.197 | | 0.226 | | 0.211 |
| Pilot C | | | | | | | | |
| 147 | 684 | -0.222 | 138 | 0.029 | 281 | -0.045 | 265 | -0.570 |
| 148 | 651 | -0.293 | 200 | -0.094 | 177 | -0.080 | 274 | -0.416 |
| 149 | 717 | -0.047 | 178 | 0.533 | 237 | -0.098 | 302 | -0.450 |
| 150 | 739 | -0.090 | 184 | 0.255 | 212 | 0.084 | 343 | -0.179 |
| 151 | 470 | -0.089 | 135 | 0.378 | 123 | -0.150 | 212 | -0.463 |
| 152 | 522 | -0.203 | 125 | 0.051 | 129 | 0.383 | 268 | -0.536 |
| 153 | 517 | -0.060 | 124 | 0.498 | 178 | 0.404 | 215 | -0.641 |
| 154 | 504 | 0.008 | 105 | 0.640 | 161 | -0.483 | 238 | -0.438 |
| | Mean | -0.125 | | 0.286 | | 0.002 | | -0.462 |
| | SD | 0.103 | | 0.269 | | 0.291 | | 0.137 |
| Pilot D | | | | | | | | |
| 116 | 769 | 0.116 | 323 | 0.178 | 202 | -0.077 | 244 | 0.108 |
| 117 | 757 | -0.076 | 197 | 0.348 | 318 | -0.322 | 242 | -0.111 |
| 118 | 769 | -0.029 | 224 | 0.159 | 289 | -0.064 | 256 | -0.058 |
| 119 | 760 | -0.027 | 187 | 0.218 | 334 | 0.120 | 239 | -0.368 |
| 128 | 452 | 0.405 | 108 | 0.207 | 161 | 0.431 | 183 | 0.425 |
| 129 | 481 | 0.008 | 128 | 0.510 | 135 | -0.104 | 218 | -0.131 |
| 130 | 486 | -0.034 | 123 | 0.514 | 155 | -0.245 | 208 | -0.130 |
| 132 | 456 | 0.468 | 107 | 0.104 | 161 | -0.113 | 188 | -0.023 |
| 133 | 498 | -0.088 | 135 | 0.309 | 160 | 0.188 | 203 | -0.195 |
| 134 | 511 | -0.042 | 118 | 0.334 | 202 | -0.075 | 191 | -0.089 |
| 135 | 529 | -0.012 | 122 | 0.512 | 188 | -0.489 | 219 | -0.569 |
| | Mean | 0.063 | | 0.308 | | -0.068 | | -0.104 |
| | SD | 0.193 | | 0.150 | | 0.250 | | 0.251 |

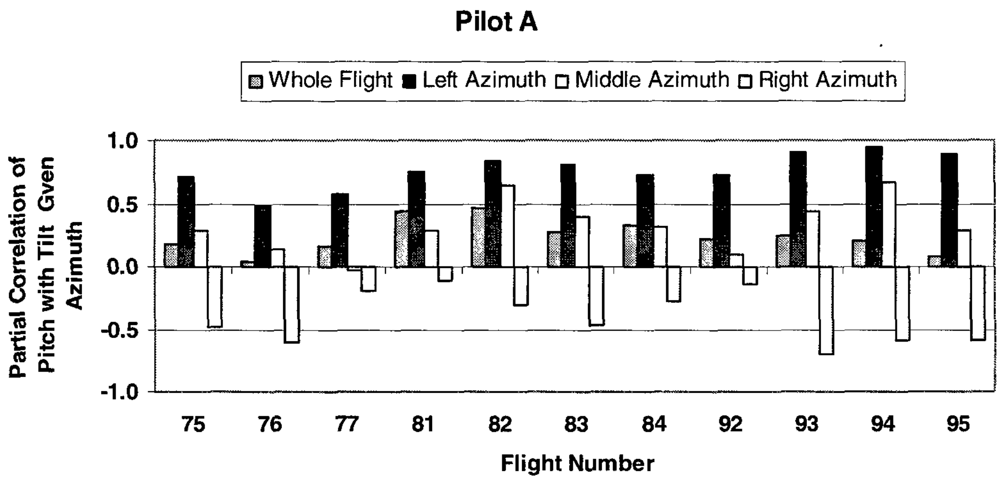



Figure 26. Partial correlation of head pitch with head tilt adjusted for head azimuth for each of Pilot A's 11 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within $\pm$ 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

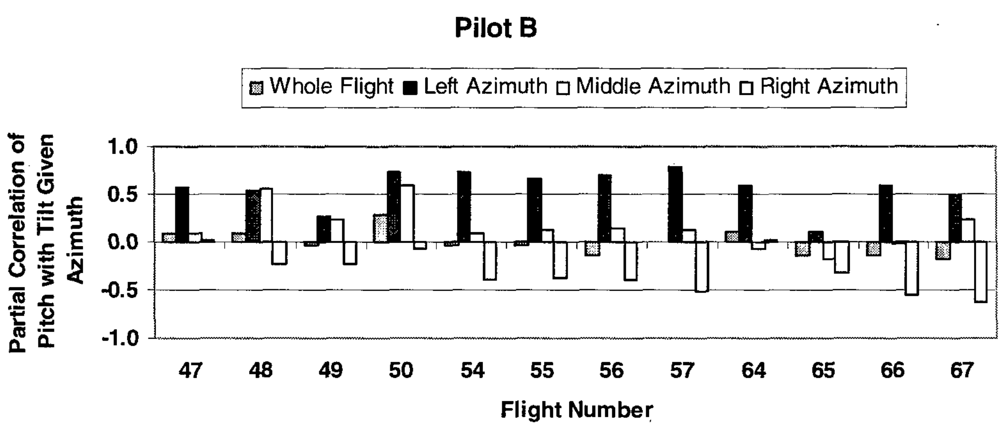



Figure 27. Partial correlation of head pitch with head tilt adjusted for head azimuth for each of Pilot B's 12 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within $\pm$ 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

Pilot C

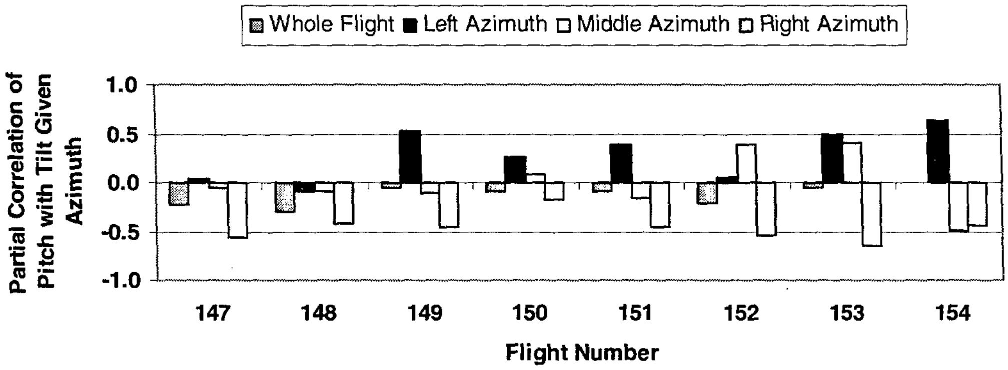



Figure 28. Partial correlation of head pitch with head tilt adjusted for head azimuth for each of Pilot C's 8 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

Pilot D

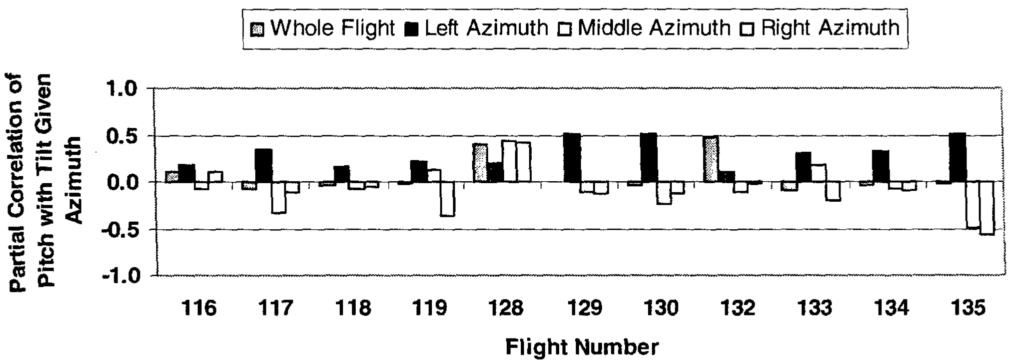



Figure 29. Partial correlation of head pitch with head tilt adjusted for head azimuth for each of Pilot D's 11 flights as identified on the abscissa. Four correlations are shown for each flight: The left bar of each group is the correlation calculated over the whole flight; the second bar of each group is the correlation calculated when the head was turned more than 10° to the left; the third bar is the correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the correlation calculated when the head was turned more than 10° to the right.

Specifically, partial correlations of head pitch with head tilt, corrected for any contribution from head azimuth, were calculated. These partial correlations are in Table 3 individually for each flight for Pilots A through D in exactly the same fashion and format as in Tables 1 and 2. These partial correlations are illustrated in Figures 26, 27, 28, and 29 individually for each flight for Pilots A through D, respectively. The means and standard deviations of these partial correlations were calculated and are the histograms of Figure 30, and are directly comparable to the histograms of Figure 25. As can be seen by comparing the appropriate graphs of the individual pilots as well as the averages in Figures 25 and 30, the correction of the correlation between head azimuth and pitch has little to no impact on the correlations between head pitch and head tilt seen across the four pilots' individual flights. This shows that the relationship between head pitch and head tilt was not inflated by any occasional contribution from the consistently stronger relationship of head azimuth to head tilt.

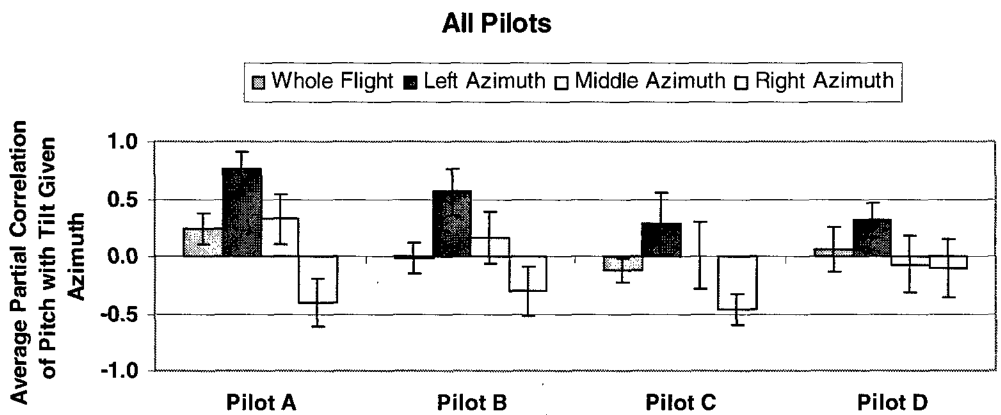



Figure 30. Partial correlation coefficients between head pitch and head tilt adjusted for azimuth averaged across all flights for each of the four pilots. Four averages are shown for each pilot: The left bar of each group is the average correlation calculated over the whole flight; the second bar of each group is the average correlation calculated when the head was turned more than 10° to the left; the third bar is the average correlation calculated when the head was within ± 10° of straight ahead; and the fourth bar is the average correlation calculated when the head was turned more than 10° to the right. The error bars show ± 1.0 S.D.

## Discussion

The database contained the slalom flight task that was parsed from full flights lasting about 90 minutes each and consisting of six different flight maneuvers. The shortest slalom was completed within 42 seconds and the longest required nearly 80 seconds to complete. Although the database does not provide a way of plotting head position as a function of the status of the aircraft on a second-by-second basis, the database does show what the pilot must have been doing to perform the assigned task

over the 40- to 80-second interval required of the slalom. Studies of OKCR reported in the literature routinely use head tilts recorded and averaged over flight intervals much longer than the 42- to 80-seconds required for the slalom. For example, Patterson (Patterson, 1995; Patterson et al., 1997) averaged head tilts over maneuvers ranging from about 1.5 minutes to over 15 minutes. The sorties flown in Smith's study (Smith, 1994; Smith, 1997) lasted about 13 minutes. Braithwaite and his colleagues (Braithwaite et al; 1997a, b) used several maneuvers, ranging from about 3 to 8 minutes in duration. By comparison with OKCR literature, the head tracking database analyzed for the present paper, containing only the one maneuver, provided a clear picture of the required flight task with a finer grain of temporal resolution.

Although actual aircraft bank angles had been removed from the available database, making it impossible to plot head tilt as a function of aircraft bank angle, as is typically found in OKCR literature, an approximation is possible. The pilots successfully executed the slalom; therefore, at a minimum, the pilots must have controlled the aircraft to produce the requisite pair of left turns followed by the requisite pair of right turns. These pairs of left and right turns were clearly reflected in the head tracking database. The head azimuth record showed that the pilots' heads turned twice to the left, then twice to the right, and that the temporal characteristics of each of these turns were completely consistent with the slalom. Furthermore, according to OKCR literature, each left bank of the aircraft should produce a right head tilt and each right bank of the aircraft should produce a left head tilt, and this was found to be the case as well. During the interval in which the pilots performed the slalom, they tilted their heads to the right twice and to the left twice, exactly as predicted by the OKCR literature.

The analysis of the database demonstrates a consistent relationship between the turning and tilting of the pilot's head as is clearly shown in Figures 4 through 13. Specifically, a head tilt to the right occurred coincidently with a head turn to the left, and a head tilt to the left occurred coincidently with a head turn to the right. On one hand, this relationship should be no surprise. The pilot was controlling the aircraft through a rather aggressive turn. In this situation, the pilot should be looking where the aircraft is heading, into the direction of the turn, rather than looking straight ahead out of the cockpit over the nose of the helicopter as it turns through the world. Consequently, as the data showed, the pilots turned their heads to the left for each left turn and to the right for each right turn. Furthermore, as shown in Figure 13, as the head turned, there was a strong propensity for it to tilt as well.

The relation between head tilt and head turn has received scant attention in OKCR literature. To our knowledge, only one study in this literature discussed the possible impact of head turn on head tilt (Gallimore et al., 1999). That study discussed the consistent finding that OKCR head tilts asymptote with values of about 15° to 20° for aircraft bank angles of about 40° to 45°. When aircraft bank angle exceeds this maximum value, head tilt angle decreases, in an apparently reliable fashion. The authors noted the fact that the maximum head tilt angle of 15° to 20° is not a physiological ceiling since anthropometric studies show the average human male head can tilt to about 40° (Merryman, 1997; Merryman and Cacioppo, 1997). They suggested that part of the

explanation for the decrease in head tilt with aircraft bank angles greater than 45° may be due to the impact of head azimuth. "A very likely explanation is related to the results of head yaw movements. When flying VMC [visual meteorological conditions] and making turns around way points, pilots turn their head (yaw) in the direction of aircraft bank. The purpose of this movement is to keep the way point as a visual target during the turn. When the head is in this yawed position, angles of possible head tilt are reduced by anatomical limitations" (Gallimore et al., 1999). These authors seem to be suggesting that, at least for the extreme head azimuths, head azimuth works against head tilt.

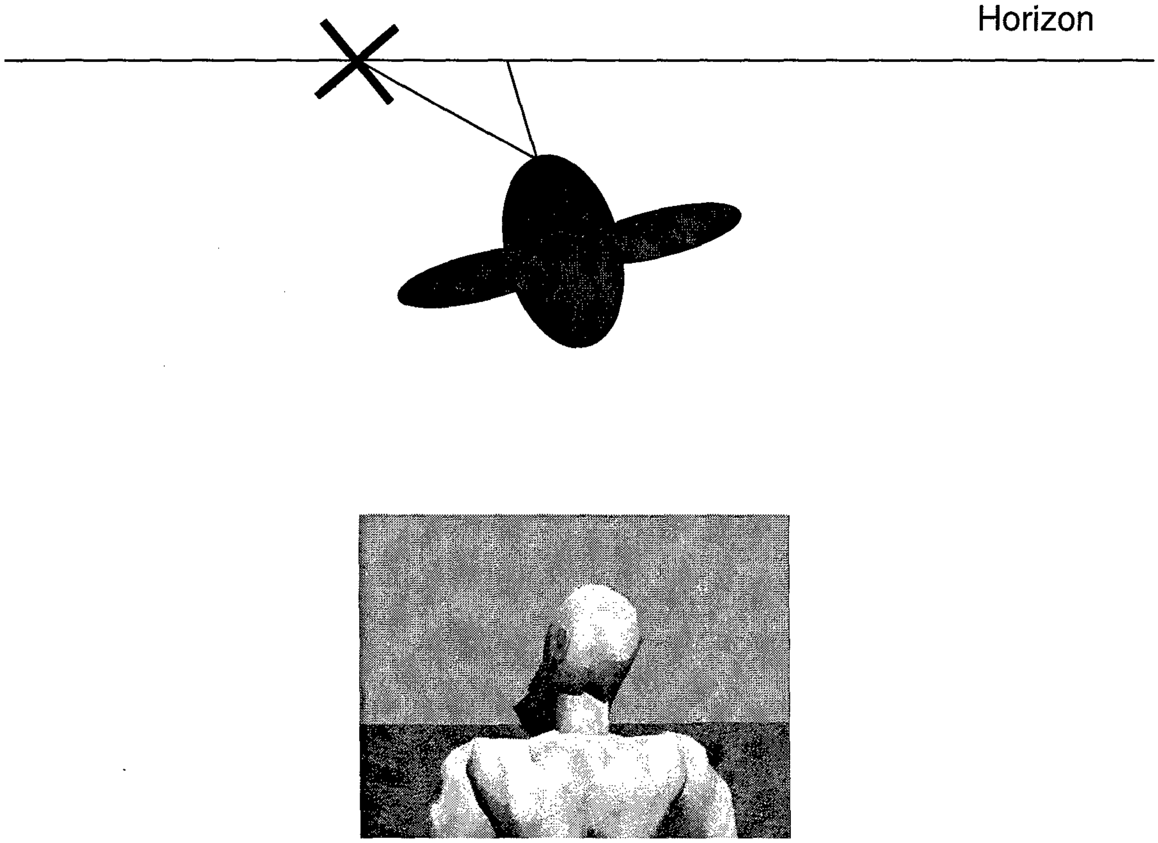



Figure 31. When the aircraft banks and turns, the data show that the pilot's head turns to enable the pilot to look into the turn. This turn of the head is associated with the head's tilt.

An alternative view is that head tilting and head turning do not work in opposition. Quite the contrary, they may work closely together, since head tilt and head turn are so highly correlated. It is possible that, at least under VMC, the head turn, which is required to keep the way point in view for the pilot, and the coincident head tilt are different aspects of the same head motion. If this is true, then the separation of the head motion into the two orthogonal axes of head turning and head tilting may reflect more the convenience of the head tracking instrumentation rather than reflect a pair of separable biomechanical responses. This suggests that, to the extent that head tilt and azimuth are correlated, they may be different aspects of the same head movement that a pilot makes

in order to keep the way point in view. This hypothesis, illustrated in Figure 31, suggests that the observed head tilt frequently attributed to the OKCR is, at least to some extent, a product of the biomechanical cross-coupling of head azimuth and tilt.

If this biomechanical cross-coupling hypothesis is true, in at least some situations, it may have important implications for understanding OKCR, which currently is discussed in the literature as a visually driven neck reflex, hence its name, opto-kinetic cervical reflex. It is thought to be an involuntary behavior that occurs without conscious volition; although, like many other reflexes, it may be consciously modulated. The stimuli for this neck reflex are thought to be visual, as distinct from vestibular, and the appropriate visual stimulus for eliciting OKCR is usually described as the tilting of the horizon that occurs when an aircraft, or some other vehicle such as a bobsled, rolls into a turn (Merryman, 1997; Merryman and Cacioppo, 1997; Smith, 1994; Smith 1997). The OKCR is thought to reposition the visual horizon on the horizontal meridian of the visual field, which presumably provides a more natural visual frame of reference, and thereby decreases the likelihood of spatial disorientation and control reversals. Several researchers have hypothesized that OKCR is primarily driven by stimuli presented in the periphery of the visual field, a suggestion based on a literature describing motion perception in the visual periphery (e.g., Brandt, Dichgans and Koenig, 1973; Held, Dichgans, and Bauer, 1975; Young et al, 1984; Young, Shelhamer, and Modestino, 1986).

The expected dependence of OKCR on peripheral visual stimulation has been specifically tested in a pair of studies designed to assess the strength of OKCR as a function of the amount of the field of view (FOV) visible outside the cockpit (Gallimore et al., 1999, 2000). Both studies used 40°, 60 °, and 100° FOVs, but neither of these studies showed OKCR response to be impacted by these different FOV sizes. The investigators did attempt to reconcile these negative results with the hypothesis that OKCR depends on the stimulus FOV by comparing results across several studies; but these studies were conducted by different investigators, with different subjects, performing different flight maneuvers, although in some cases, with similar equipment. On the other hand, if the hypothesis proposed in the present paper is correct, there is no reason to expect that head tilt should depend on FOV. When the pilot looks into the direction of the aircraft flight path, the head simultaneously turns and tilts. The head tilt is still dependent upon a visual stimulus, of course, but the stimulus is primarily foveal, and changes in FOV should have little impact. So, the results of those studies support the present biomechanical hypothesis. This notion is completely consistent with the observation that helicopter pilots flying a UH-60 visual simulator evidenced essentially the same amount of head tilt under daytime visual flight or under simulated night conditions with NVGs and the relatively restricted 40° circular FOV they provide (Braithwaite et al., 1997a, b).

There are other results in the literature that are difficult to reconcile with the view that OKCR is primarily a reflex driven by visual stimulation of the peripheral field. One study, for example, compared the magnitude of OKCR for the same pilots under two conditions in a visual flight simulator (Smith, 1994; 1997). Under one condition, the

pilot controlled the aircraft under VMC at altitudes less than 900 feet above ground level. Under the other condition, the same person performed navigator-type tasks, viewing waypoints, traffic, and terrain, but did not control the aircraft. The experiment was designed to test the hypothesis that OKCR head tilt would be greater when individuals were controlling the aircraft than when they were merely passively observing the visual world. This expectation was motivated in part by the idea that the pilot would need a more precise view of the world than would the passive observer; consequently, OKCR would provide the natural vertical and horizontal orientation. But the results were in the opposite direction; the magnitude of the head tilt was significantly less when the pilots were actively controlling the aircraft than when they were merely noting the waypoints, traffic, terrain, and other features of the out-the-cockpit view. The author considered these results to be counterintuitive and proposed a relatively complicated post hoc explanation based on task requirements and the accentuation or attenuation of the expected reflexive behavior by the required motor responses.

On the other hand, these results seem completely consistent with the biomechanical hypothesis proposed in the present paper. When the pilots were not flying the aircraft, they were instructed to actively search the out-the-window view, looking for specifics in the terrain and airspace. In other words, they were encouraged to look around, and presumably they moved their heads in the process. When they were controlling the aircraft they were looking for specific flight relevant waypoints, and were engaged in the tasks posed by flying. The results suggest that these individuals were merely making more frequent, and possibly greater head movements, when they were in the more 'passive' role than when they were the pilot in control of the aircraft.

Two studies using a visual flight simulator have assessed OKCR with HMDs, but neither study found any evidence of an OKCR head tilt, even under conditions of flight in good visibility (Liggett and Gallimore, 2001; Liggett, 2002). The authors explained these surprising results in a very similar fashion; the pilots were using the HMD symbology to control the aircraft through the assigned maneuvers rather than attending to out-the-window views of the visual world. The authors claimed that specific demands of the flight task and attention can modulate the presumably reflexive mechanisms underlying the anticipated OKCR. The hypothesis advanced in the present paper suggests that the dependence of OKCR on visual stimuli may have little to do with attention, cognitive, or other higher order cognitive functions modulating a putative reflex, and more to do with the biomechanics of a turning head. If a pilot does not turn his or her head to look into the turn, a banking of the visual field may not be sufficient to induce a head tilt.

There is an additional factor to consider for the proposed biomechanical hypothesis. During a coordinated turn in level flight, the aircraft banks in the direction of the turn, causing the cockpit to roll with respect to the aircraft's longitudinal axis which, in turn, causes the external visible horizon to roll in the opposite direction. As illustrated in Figures32 and 33 during a level, coordinated, banking turn the pilot must look upward in order to see the waypoint on the horizon. Of course this upward gaze can be accomplished with the elevation of the eyes, an elevation of the head, or a combination of both. Nonetheless, as demonstrated in Tables 2 and 3 and Figures 21 through 30, when

the head is turned to the right and pitches upward to assume a posture consistent with a level, coordinated banking turn to the right, the head has a tendency to tilt in the leftward direction. Similarly, when the head is turned to the left and pitches upward to assume a posture consistent with a level, coordinated banking turn to the left, the head has a tendency to tilt in the rightward direction. This tendency for the head to tilt either to the left or right when the head is pitched was evident in the partial correlations that removed any confounding influence that the head turning behavior might have had on the observed head tilt. Clearly, as far as aircraft banking and turning is concerned, it is necessary to consider head motion in all three axes; tilt, azimuth and pitch.

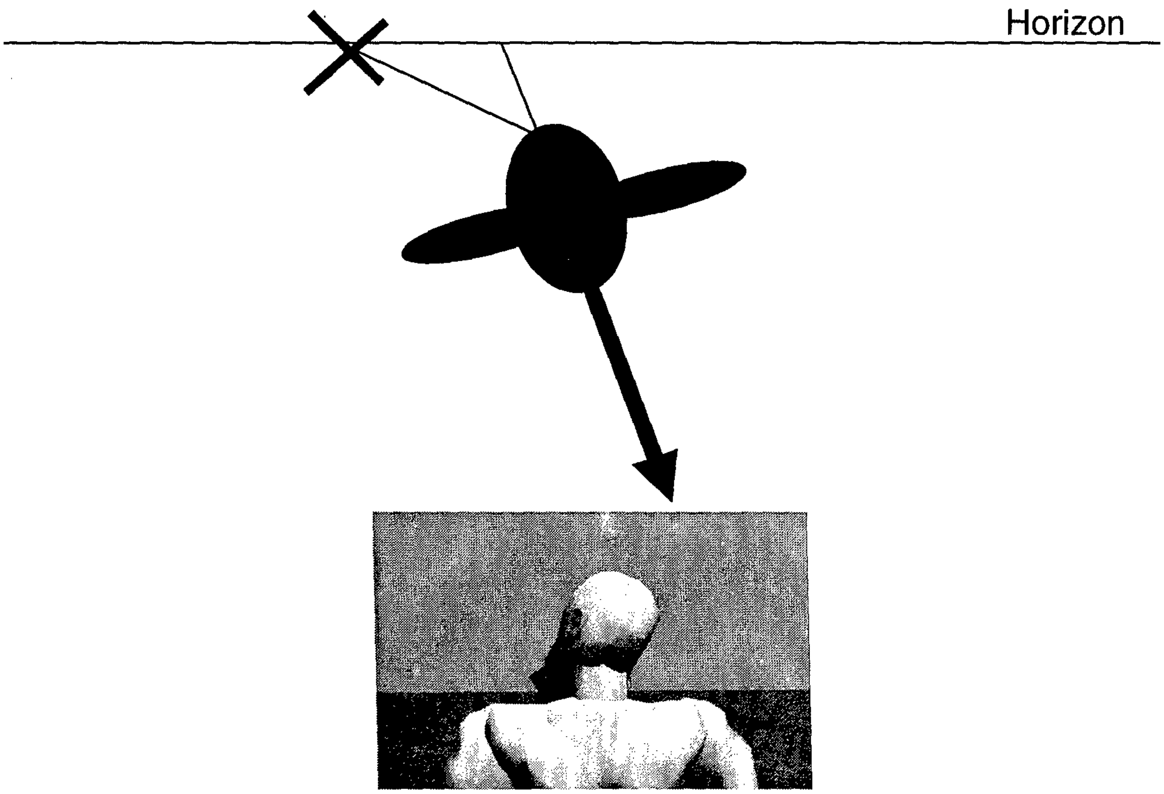



Figure 32. When the aircraft banks and turns during level coordinated flight, the aircraft's down vector is not earth normal but is essentially perpendicular to the wings.

Some studies in OKCR literature report that head elevation and head azimuth had been recorded with head tilt. Most of these studies, however, do not present these additional measures, and those few that do, present the data in the same format as OKCR head tilt. That is, head elevation or head azimuth are averaged and graphed as a function of aircraft attitude, as either pitch angle or bank angle, binned and averaged over the

discreet 5° bins. Curiously, none of these studies have considered or analyzed the cross couplings of head pitch, head tilt, and head azimuth.

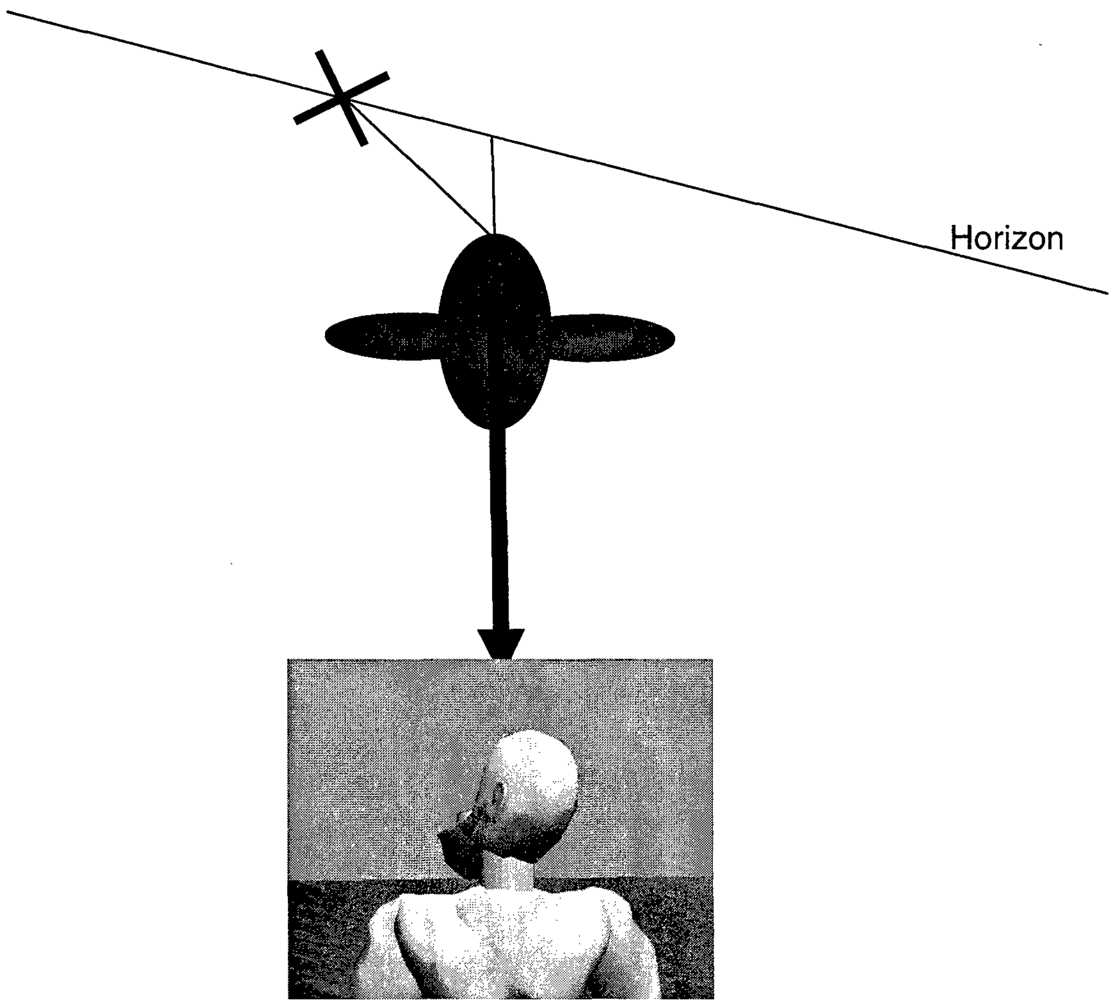



Figure 33. When the aircraft banks and turns during level coordinated flight, the pilot must look up to see the point on the horizon to which the aircraft is heading during level flight. This elevation of gaze is associated with a pitching of the head upward, which the data show to be associated with the head's turning and tilting.

The present paper has proposed an alternative to the theory that the OKCR is a neck reflex driven by specific visual stimuli. Nonetheless, it is possible that both theories are correct to some extent and both propose mechanisms that are operative; however, none of the experiments to date clearly differentiate between the two theories. All studies of OKCR, including those reported in the present paper, have demonstrated head tilt in the context of aviation, either in flight simulators or aircraft. The experimental variables these studies manipulated have been such specifics of the flight as the required flight maneuver, visibility, available cockpit flight instrumentation, and altitude. All these studies, with the exception of the present one, have used a very similar experimental

approach and data analysis strategy. These studies recorded head tilt throughout a flight and presented the head tilt as a function of aircraft bank angle, binned into 5° intervals. These studies typically graph the head tilt as a function of binned aircraft bank angles to produce curves that have a characteristic shape. A test of statistical significance, such as an analysis of variance, is commonly used to assess differences in head tilt for different aircraft bank angles.

It is surprising that none of these studies attempted to identify the parameters of the visual stimulus that are either necessary or sufficient to cause the head to tilt. The studies merely demonstrated a reliable dependence of head tilt on aircraft bank angle but provided no unimpeachable evidence that the head tilt is, in fact, dependent on such dimensions of the visual stimulus as contrast, texture, luminance, wavelength, stimulus velocity, field of view, and so forth. The demonstration of the dependence of head tilt on well-defined physical dimensions of the eliciting visual stimulus would be necessary before the observed behavior could be attributed convincingly to a newly discovered reflex involving relatively high order neuromuscular mechanisms.

These issues have practical implications. For example, the identification of the visual stimulus dimensions necessary and sufficient for evoking the response (or eliciting the reflex) could provide a basis for establishing design and engineering specifications for such graphical display systems as those used for avionics, simulation, and training. One could argue that such visual displays should be capable of eliciting or evoking behaviors normally seen in the operational environment, particularly behaviors that are reflexive. It might be possible that the elicitation of such behaviors could provide a metric for designing and evaluating the effectiveness of cockpit symbology. Such a metric presupposes an understanding of the mechanisms driving the behaviors.

Much of the interest in the OKCR arises because it is thought to contribute to at least some episodes of spatial disorientation (SD) (e.g., Gallimore et al., 1999; 2000; Patterson 1995; Patterson et al., 1997). It has been argued that the real horizon, when visible outside the cockpit during a banking turn, causes the head to tilt in a reflexive fashion; whereas the artificial horizon inside the cockpit does not. This difference means that the pilot's head could change orientation when transitioning between visual and instrument flight. This reorientation may cause a change in the pilot's perception of the horizon information, a change that could contribute to SD. Differences among heads-down (HDD), heads-up (HUD), and head-mounted (HMD) displays complicate these issues. Although the HDD and the HUD remain stationary with respect to the aircraft, the HMD does not. It is mounted on the head and moves with it. Since the HMD is tethered to the head, it may be necessary to compensate HMD horizon and aircraft attitude information when the head tilts. Consequently, a pilot's head motions and posture, including tilt, may affect the display of aircraft attitude information in a HMD in a fashion that is different for the display of the same information in a HDD or HUD. This differential impact of head motion on the display of the same information may add to the difficulty of transitioning between visual and instrument flight and between display types. Symbology effective with one type of display may not be effective with another.

It has been noted that sometimes when a pilot makes the initial control input to roll the aircraft out of a banking turn, the input may be in the wrong direction, causing the aircraft to roll in the wrong direction, increasing rather than decreasing bank angle (Braithwaite et al, 1997a, b; Gallimore et al., 1999). Such erroneous inputs are often identified as control input reversal errors. Some investigators have argued that these reversal errors may result from the pilot's momentary confusion concerning whether the joystick input controls the horizon or the aircraft. From the vantage point of the pilot in the cockpit, the aircraft seems to be the stationary component whereas the horizon seems to be the moving component. For example, movement of the joystick to the left would roll the aircraft to the left out of a rightward bank; but from the pilot's vantage point, this would cause the horizon to seem to rotate to the right. Some have argued that the OKCR head tilt may contribute to the momentary confusions thought to underlie the control input reversal errors. In this context, the control input reversal errors may be a leading indicator of SD, exacerbated by the OKCR. On the other hand, it should be noted that in at least some situations the control reversals may reflect a valid decision making strategy rather than confusion per se (Liggett, 2000). That is, some pilots may have decided on a decision strategy that lets the aircraft tell them whether the direction of the control input is correct or not. In this case, the pilots respond first, then detect whether the response increases or decreases the error with a subsequent response appropriate for the error. Therefore, it would seem that not all control input reversals should be thought of as errors. Furthermore, the relationships among SD, control input reversal, and head tilt have yet to be clearly established. An evaluation of the impact of head tilt on SD and control input reversals depends on a clarification of the roles of the visual stimulus and its various parameters in driving the response. Considering the presumed importance of the horizon for driving the OKCR, with its possible role in SD, and impact on HMD symbology, it seems reasonable to determine first the extent to which the OKCR is, in fact, a visual response.

A specific shortcoming of the present study is that the data were only from four pilots; however, the costs and logistical obstacles confronting these types of flight tests make the data obtained from such studies all the more valuable. Arguably, there is an ethical responsibility to use such archived data to address important issues whenever possible. Despite the small number of pilots in the study, the data base contains a large number of repeated flights from each one of these expert pilots, so that the consistency of the results can be judged. The head tracking data archived in the appendices show substantial variability in the data set; yet the dependence of head tilt on head azimuth is clearly evident through all the variability. The dependence on head pitch was less clear and correspondingly less definitive, and required a more careful and sophisticated analysis. The primary purposes for which the database had initially been collected had nothing to do with the analyses reported here, which makes it all the more noteworthy that the analysis here is so unambiguous. Nonetheless, the primary purpose of the present paper is to advance an alternative, biomechanical hypothesis for the mechanisms underlying phenomenon commonly attributed to the putative OKCR. Clearly, many more issues need to be addressed for evaluating the relative merits of the two hypotheses.

The model proposed in the present paper may seem to deemphasize the importance of visual stimuli for head tilts and related phenomena. Nonetheless, head posture may still be important for 'roll compensation,' HMDs, and other advanced visual display technologies, even if the observed head tilt phenomena turn out to be more a consequence of the mechanics of head turning and less a reflex driven by such visual stimulus parameters as luminance, field location, size, spatial, temporal, or chromatic spectra, and so forth. In fact, if the biomechanical hypothesis proves correct, head tilt phenomena could even be all the more important for display technologies since the head tilts would be ubiquitous with head movements, while being relatively independent of visual stimuli. This would imply that the impact of head movement would have to be considered for the design of informational displays for many environments in which the head is free to assume a range of postures. This could be particularly important for applications that couple the display with the head. The phenomenon originally described as OKCR would then be important not only for aviation but for many non-aviation environments in which the horizon itself may be of negligible importance.

## Summary

The literature describes the OKCR as a reflex tilting of a pilot's head that occurs when the pilot executes a coordinated banking turn under VMC. During such a turn, for example rolling the aircraft into a left bank so that it turns left, the horizon appears to the pilot to roll in the opposite direction and tilt to the right. But of course the horizon is not really moving, the aircraft is. Nonetheless, the apparent tilting of the horizon is thought to drive the reflex tilting of the pilot's head to keep it normal with the horizon. When the horizon seems to tilt, the pilot's head tilts to remain approximately perpendicular to it, or at least that is the widely accepted current model. This model describes the OKCR as (1) a reflex neck movement, (2) primarily driven by stimulation in the periphery of the visual field, (3) that serves the specific purpose of providing a stabilized horizontal frame of reference, and (4) important for maintaining spatial orientation.

The literature describes the OKCR as potentially contributing to episodes of spatial disorientation and dangerous control input reversal errors. The head tilting may be important for the design of head mounted display systems and symbology since these systems may be referenced to either the tilting head or the aircraft. The choice is particularly important for the display of aircraft attitude information, which is most commonly referenced to the horizon.

The present paper describes an alternative explanation for the observed head tilting behavior of the pilot attributed to the OKCR. The head tilting behavior of pilots that occurs when an aircraft banks and turns under VMC may be understood more parsimoniously as the result of the requirement of the pilot to look into the direction of the turn. Effective control of aircraft requires pilots to see where they are going. This requirement means that pilots should look to the left when the aircraft turns left, and to look to the right when the aircraft turns right. It is easier for a pilot to look in these directions if there is a head turn along with the gaze shift. Not surprisingly, the data showed this. The data also showed a high correlation between the head turning and head

tilting of the pilots. A right turn of the head was reliably and consistently associated with a left tilting of the head, and conversely, a left turn of the head was reliably and consistently associated with a right tilting of the head.

The implication is that the head tilt, previously attributed to OKCR as a visually driven neck reflex, is more simply understood as the result of the way the head moves when pilots in a turning aircraft simply are looking where they are going. The OKCR model attributes the head tilt to a peripheral visual stimulus. On the other hand, the alternative biomechanical model presented here predicts that head tilting behavior would be found with head turns, even in the absence of visual stimuli. This difference is crucial and may have important implications for the design and use of head mounted informational displays in a large number of contexts.

The new biomechanical model pilot head tilting behavior is based on the analysis of an archived database containing the head movement (azimuth, pitch and tilt) records of four military pilots as they executed a slalom flight maneuver in an AH Mk 7 Lynx helicopter under VMC. These data had been collected for purposes unrelated to the present discussion, and previous analyses addressing these original purposes have already been reported. In addition to the description of the new model based on the archived database, the present paper uses some results previously published in the literature to compare the new biomechanical model to the conventional OKCR theory.

## References

Braithwaite, M.G., Alvarez, E.A., Jones, H.D., Higdon, A.A., Groh, S.L., Beal, K., and Estrada, A. 1997a. A helicopter simulator assessment of pilot head movement during various phases of flight. Ft. Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 97-26.

Braithwaite, M.G., Beal, K., Alvarez, E.A., Jones, H.D., and Estrada, A. 1997b. The optokinetic cervico reflex during simulated helicopter flight. Aviation, Space, and Environmental Medicine. 69: 1166-1173.

Brandt, T., Dichgans, J., and Koenig, E. 1973. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Experimental Brain Research. 16: 476-491.

Craig, G. L., Jennings, S. A., and Swail, C. P. 2000. Head roll compensation in a visually coupled HMD: Considerations for helicopter operations. Aviation, Space, and Environmental Medicine. 71: 476-484.

Ercoline, W. R., DeVilbiss, C.A., and Evans, R.H. 2004. Flight displays I: Head-down display topics for spatial orientation. In Previc, F. H. and Ercoline, W. R. (Eds.), Spatial Disorientation in aviation. Vol 203: Progress in Astronautics and Aeronautics, Paul Zarchan Editor in Chief. American Institute of Astronautics and Aeronautics, Virginia 379-449.

Gallimore, J. J., Brannon, N. G., Patterson, F. R., and Nalepka, J. P. 1999. Effects of FOV and aircraft bank angle on pilot head movement and reversal errors during simulated flight. Aviation, Space, and Environmental Medicine, 70: 1152-1160.

Gallimore, J. J., Patterson, F. R., Brannon, N. G., and Nalepka, J.P. 2000. The opto-kinetic cervical reflex during formation flight. Aviation, Space, and Environmental Medicine. 71: 812-821.

Hasbrook, A. H., and Rasmussen, P. G. 1973. In-flight performance of civilian pilots using moving-aircraft and moving-horizon attitude indicators. Oklahoma City, OK:FAA Civil Aeromedical Institute. Report No. FAA-AM-73-9.

Haworth, L.A. 16 Dec. 1997. Conversation (Telephone communication) concerning roll compensation, Aeroflightdynamics Directorate, Ames Research Center, Moffett Field, CA.

Held, R., Dichgans, J., and Bauer, J. 1975. Characteristics of moving visual scenes influencing spatial orientation. Vision Research. 15: 357-365.

Jennings, S., Gubbles, A. W., Swail, C. P., and Craig, C. 1998. In flight evaluation of a fibre optic helmet mounted display. Proceedings of the SPIE. Vol. 3362: 126-135.

Johnson, S. L., and Roscoe, S. N. 1972. What moves, the airplane or the world? Human Factors. 14: 107-129.

Liggett, K. K., and Gallimore, J. J. 2001. The OKCR and pilot performance during transitions between meteorological conditions using MHD attitude symbology. Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting 115-119.

Liggett,K. K. 2000. The effect of helmet-mounted display symbology on the opto-kinetic cervical research, frame of reference, and pilot performance. Ph.D. Dissertation. Wright State University Dayton, OH.

Liggett, K. K. 2002. The effects of helmet-mounted display symbology on the opto-kinetic cervical reflex and frame of reference. RTO Meeting Proceedings 86: Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures. LaCoruna, Spain 15-17 April 2002.

Melzer, J. E., and Moffitt, K. 1997. Head mounted displays: Designing for the user. New York, McGraw Hill.

Merryman, R. F. K. 1997. The optokinetic cervical reflex (OKCR) in pilots of high-performance aircraft. Wright Patterson Air Force Base, OH: Armstrong Laboratory, Crew Systems Directorate. Report No. AL/CF-1997-0082.

Merryman, R. F. K., and Cacioppo, A. J. 1997. The optokinetic cervico reflex in pilots of high-performance aircraft. Aviation, Space, and Environmental Medicine. 68: 479-487.

Michael, P. R., Jardine, T. E., and Goom, M. K. 1978. Visual effects of helicopter maneuver on weapon aiming performance. Operational Helicopter Aviation Medicine, AGARD, 25/1-25/15.

Patterson, F. R. 1995. Aviation spatial orientation in relation to head position and attitude interpretation. Ph.D. Dissertation. Wright State University Dayton, OH.

Patterson, F. R., Cacioppo, A. J., Gallimore, J. J., Hinman, G. E., and Nalepka, J. P. 1997. Aviation spatial orientation in relation to head position and attitude interpretation. Aviation, Space, and Environmental Medicine. 68: 463-471.

Previc, F. H. 2004. Visual orientation mechanisms. In F. H. Previc and W. R. Ercoline (Eds.), *Spatial Disorientation in Aviation*. Vol 203 Progress in Astronautics and Aeronautics, Paul Zarchan Editor in Chief. American Institute of Astronautics and Aeronautics, Virginia pp 95-143.

Rash, C. E. (Editor) 1999. Helmet mounted displays: Design issues for rotary-wing aircraft. Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory.

Rostad, R. J., Rash, C. E., Briley, J. K., Mora, J. C., and Crowley, J. S. 2003. Analysis of head motion in rotary-wing flight using various helmet-mounted display configurations (Part I. Azimuth). Ft. Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2003-07.

Rostad, R. J., Rash, C. E., and Crowley, J. S. 2003. Analysis of head motion in rotary-wing flight using various helmet-mounted display configurations (Part II. Elevation). Ft. Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2003-09.

Rostad, R. J., Rash, C. E., Crowley, J. S., Briley, J. K., and Mora, J. C. 2001. Analysis of azimuth head motion in rotary-wing flight using various helmet-mounted display configurations. Proceedings of the SPIE, Vol. 4361, 115-129.

Smith, D. R. 1994. Aviation spatial orientation in relation to head position and attitude interpretation, and control. Masters thesis, Wright State University Dayton, OH.

Smith, D. R. 1997. Aviation spatial orientation in relation to head position and attitude interpretation, and control. Aviation, Space, and Environmental Medicine. 68: 472-478.

Stelle, J. A., Rostad, R. J., Rash, C. E., and Crowley, J. S. 2003. Analysis of head motion in rotary-wing flight using various helmet-mounted display configurations (Part III. Roll). Ft. Rucker, AL: U. S. Army Aeromedical Research Laboratory. USAARL Report No. 2003-13.

Stelle, J. A., Rash, C. E., Rostad, R. J., and Crowley, J. S. 2003. Roll head motion in rotary-wing flight with helmet-mounted displays. Proceedings of the SPIE, Vol. 5079, pp 382-398.

Task, H. L., and Kocian, D. F. 1995. Design and integration issues of visually-coupled systems (VCS). Wright Patterson AFB, OH: Armstrong Laboratory. AL/CF-SR-1995-0004.

Young, L. R. Oman, C. M., Watt, D. G. D., Money, K. E., and Lichtenberg, B. K. 1984. Spatial orientation in weighlessness and readaptation to earth's gravity. Science. 225, 205-208.

Young, L. R., Shelhamer, M., Modestino, S. 1986. M.I.T./Canadian vestibular experiments on the Spacelab-I mission: 2. Visual vestibular tilt interaction in weightlessness. Experimental Brain Research. 64: 299-307.

Appendix A.

Pilot A's head azimuth, pitch and tilt.

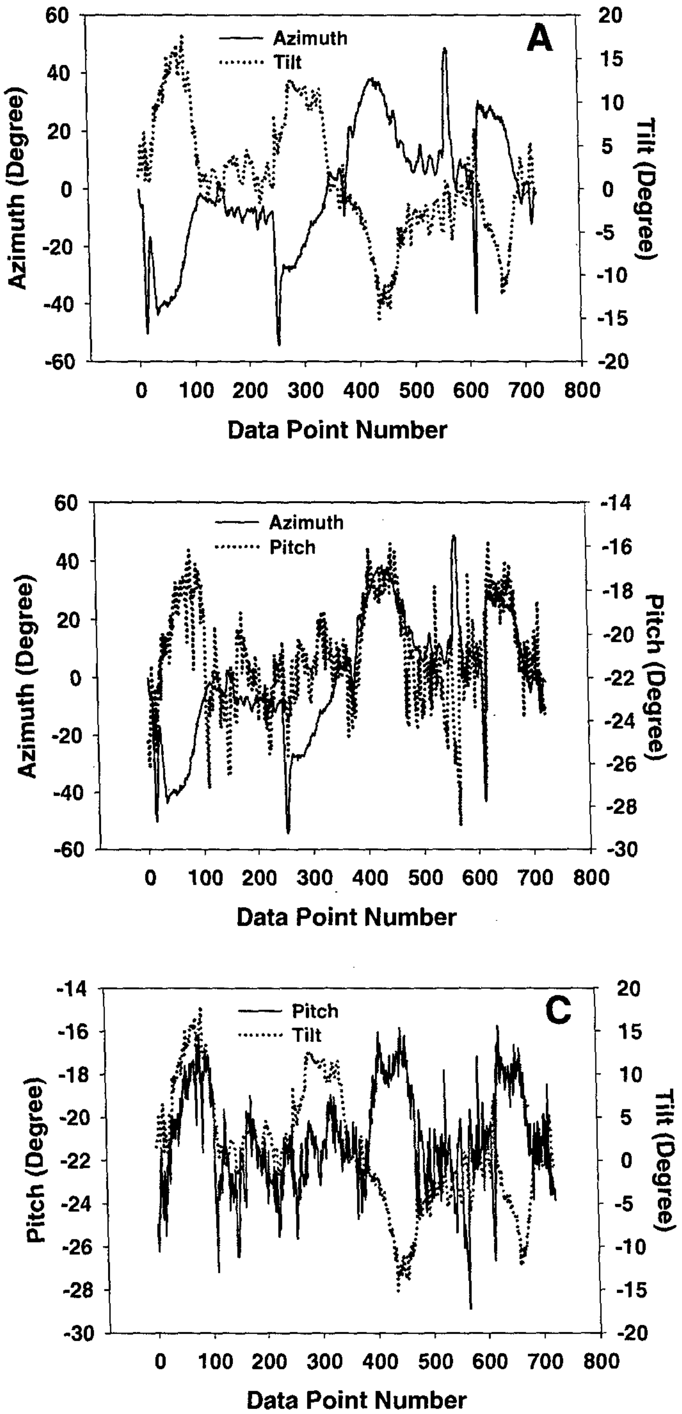



Figure A-1. Head position data from Flight 75, Pilot A's first flight, a low LOA slalom. The left axis of A shows head azimuth as the solid line while the right axis is head tilt as the dotted line; the left axis of B is head azimuth as the solid line while the right axis is head pitch as the dotted line; the left axis of C is head pitch as the solid line while the right axis is head tilt as the dotted line all in degrees and all as a function of time (10 data points = 1 second).

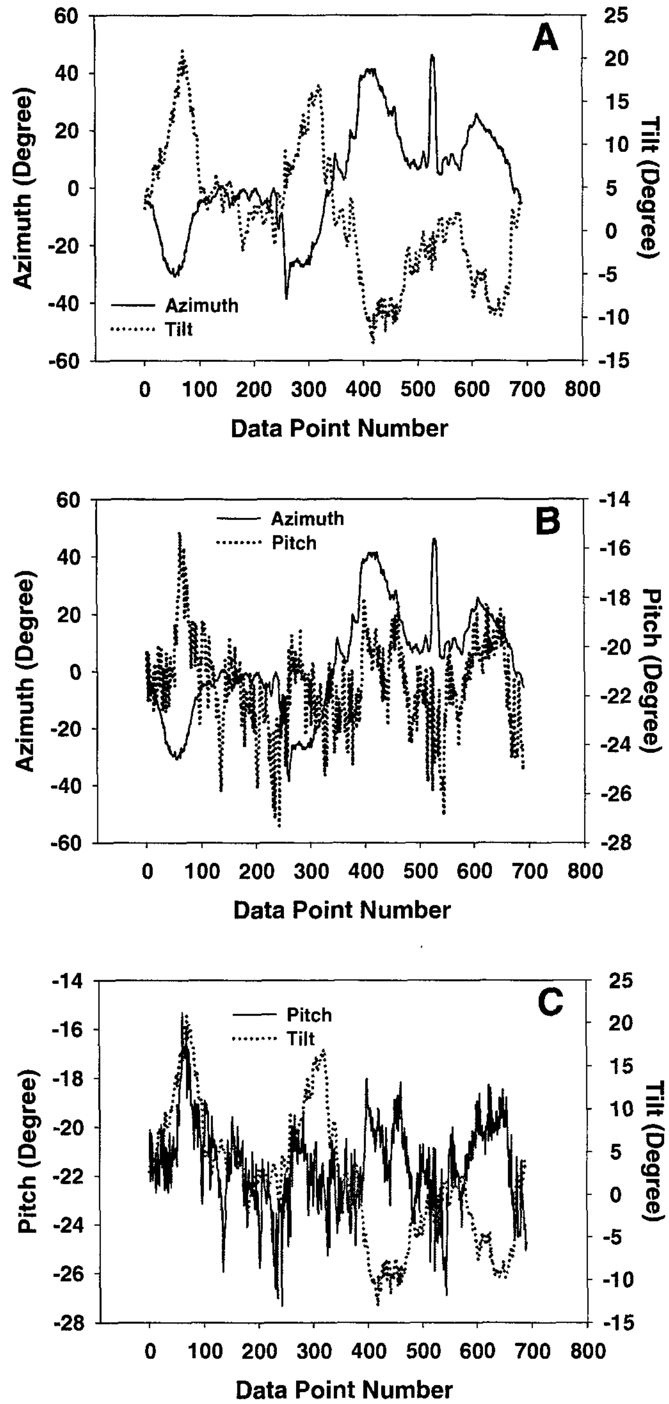



Figure A-2. Head position data from Flight 76, Pilot A's second flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

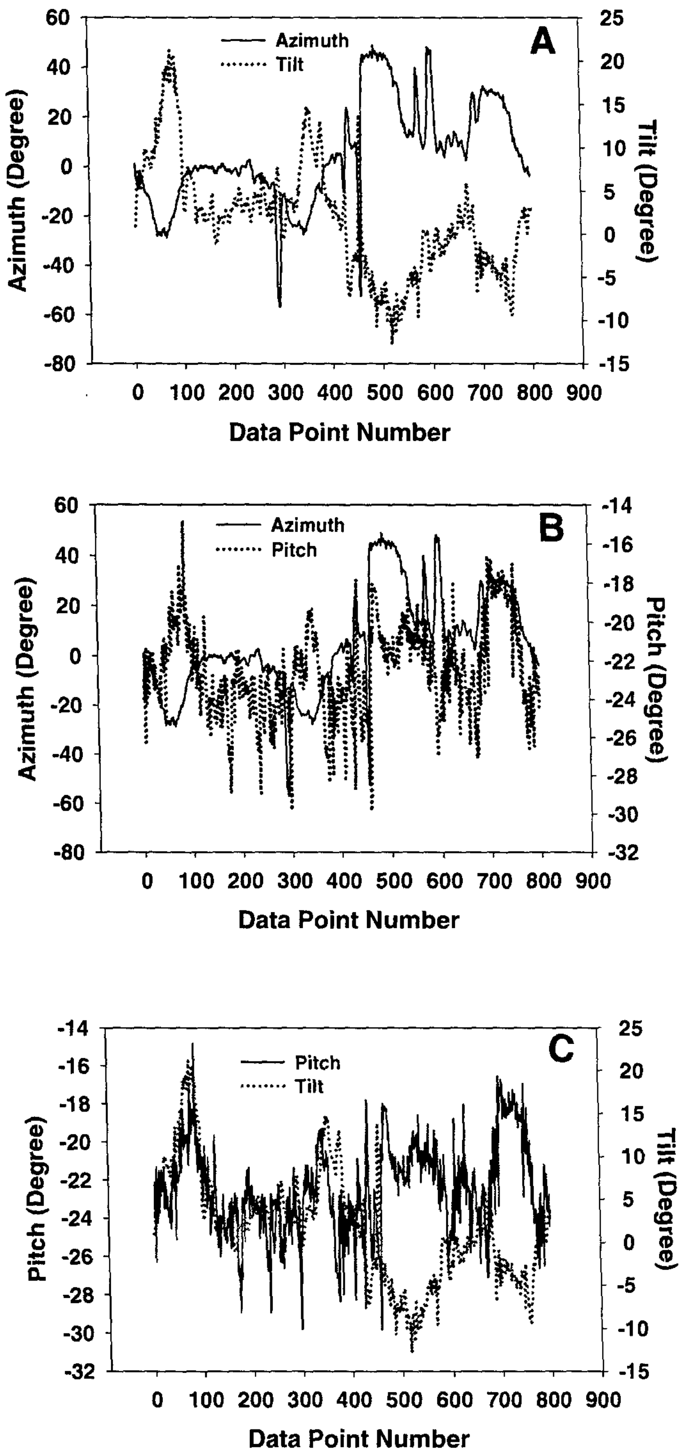



Figure A-3. Head position data from Flight 77, Pilot A's third flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

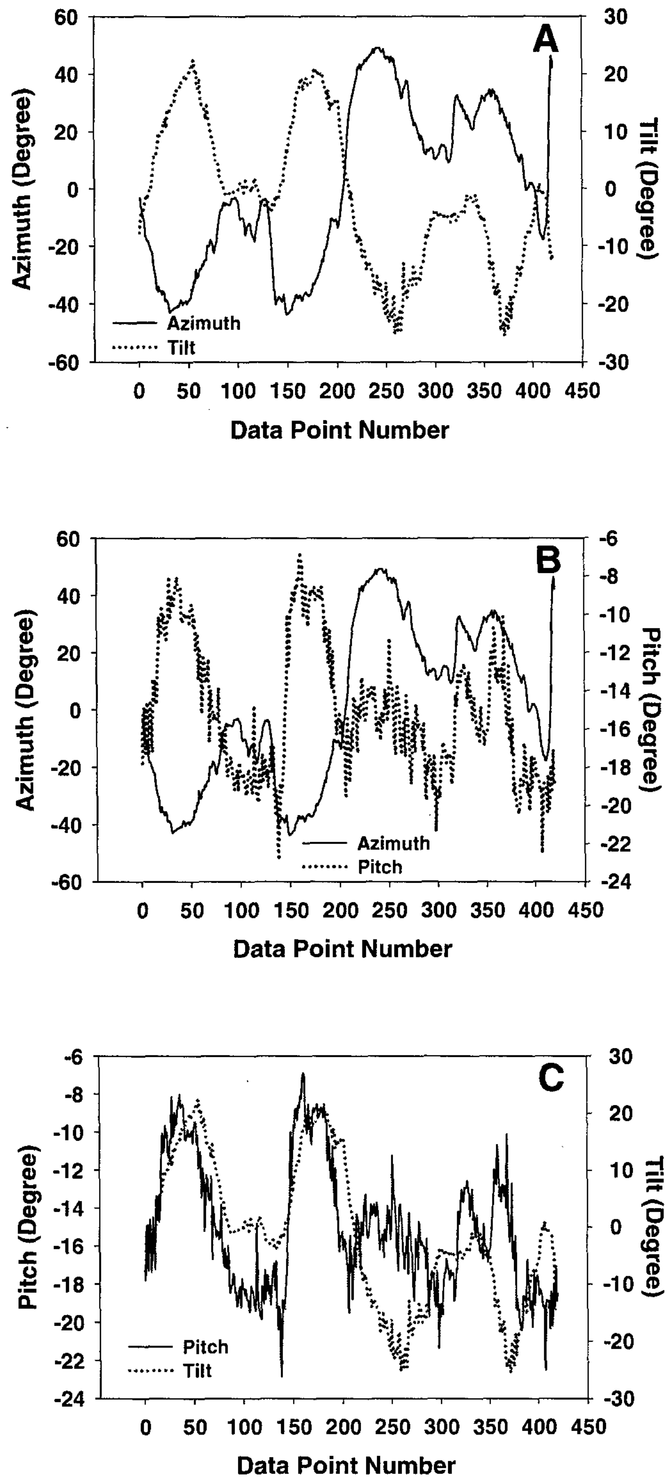



Figure A-4. Head position data from Flight 81, Pilot A's fourth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

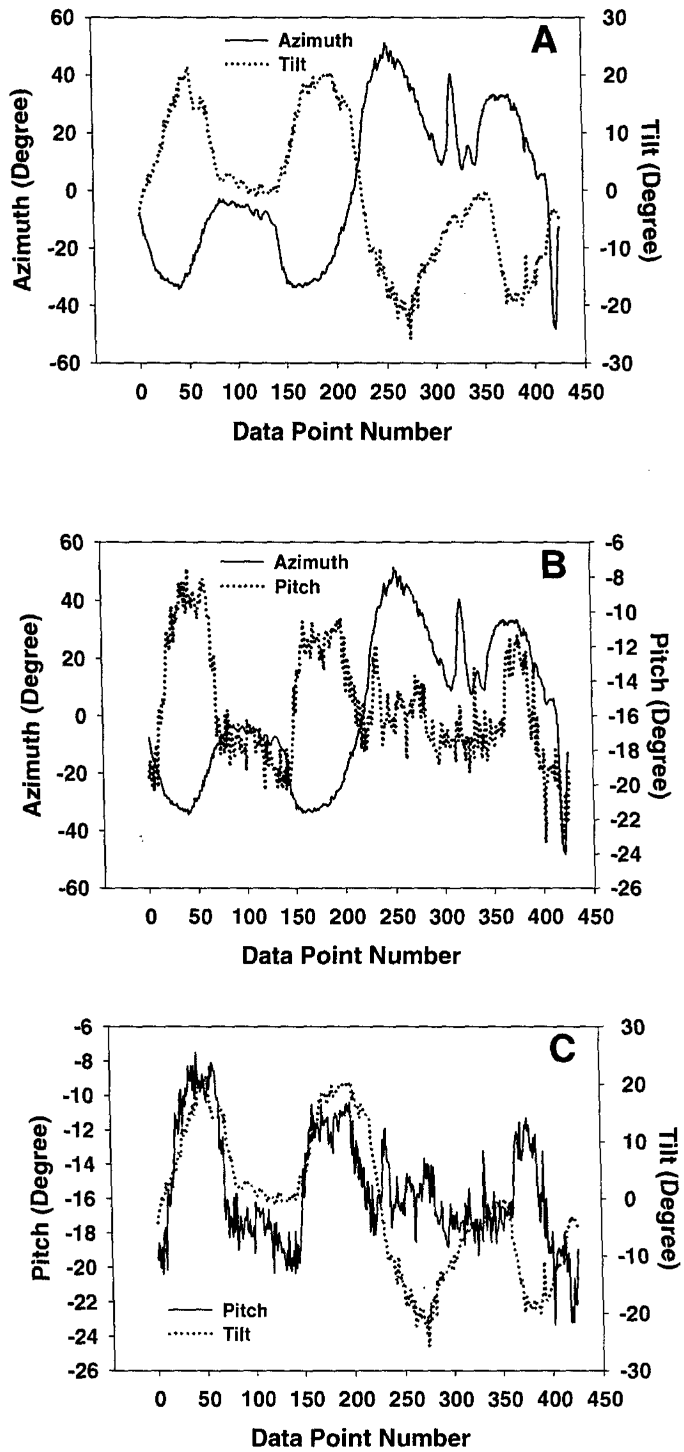



Figure A-5. Head position data from Flight 82, Pilot A's fifth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

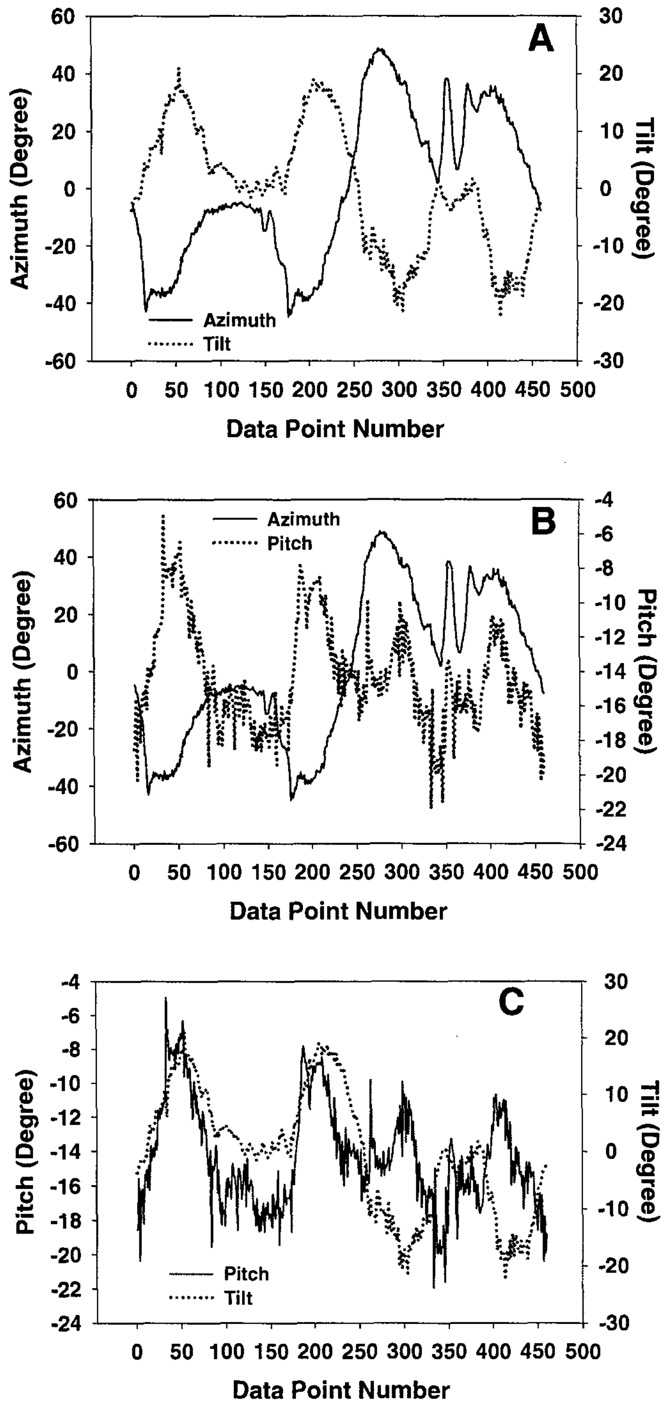



Figure A-6. Head position data from Flight 83, Pilot A's sixth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

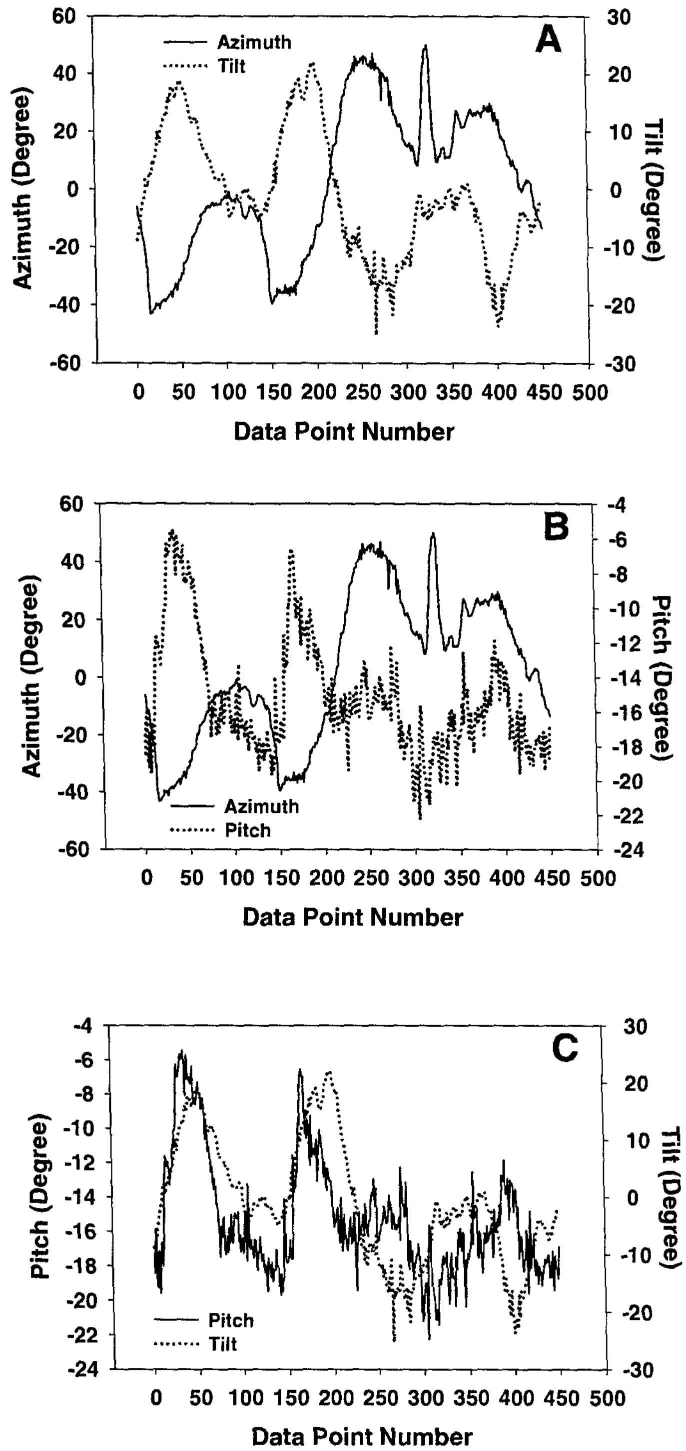



Figure A-7. Head position data from Flight 84, Pilot A's seventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

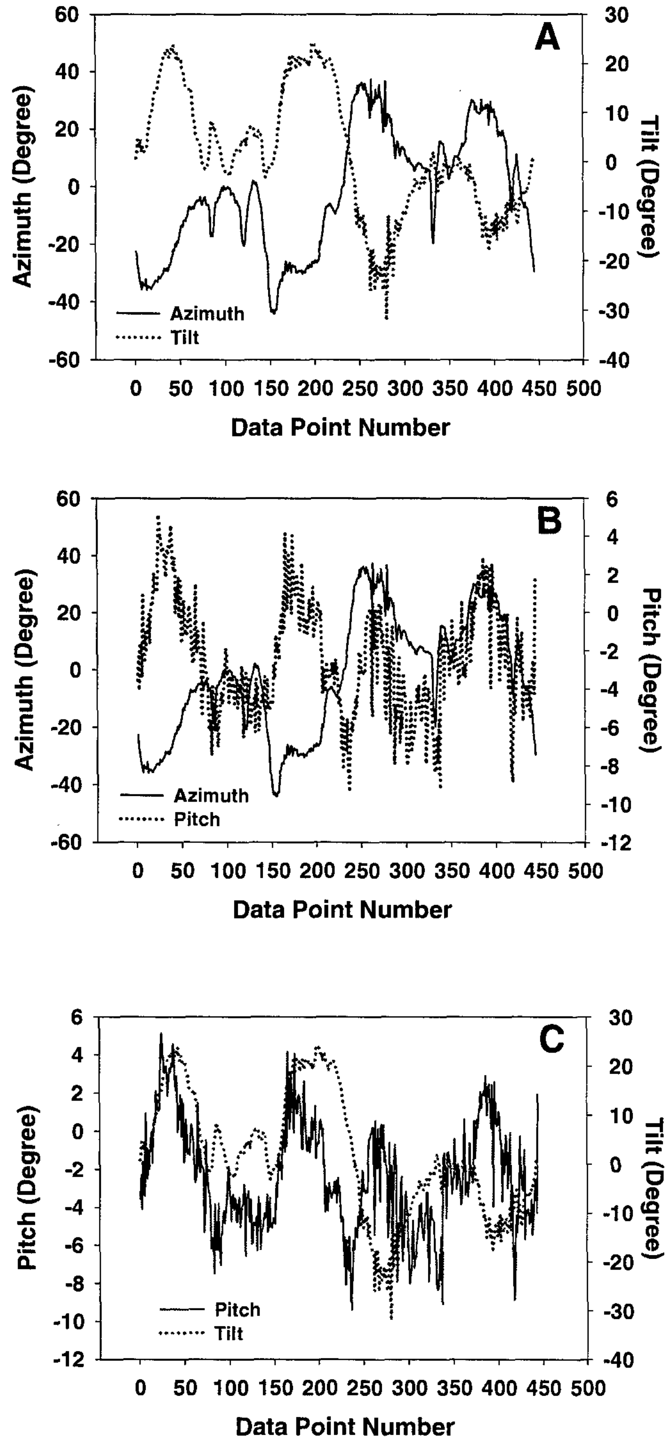



Figure A-8. Head position data from Flight 92, Pilot A's eight flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

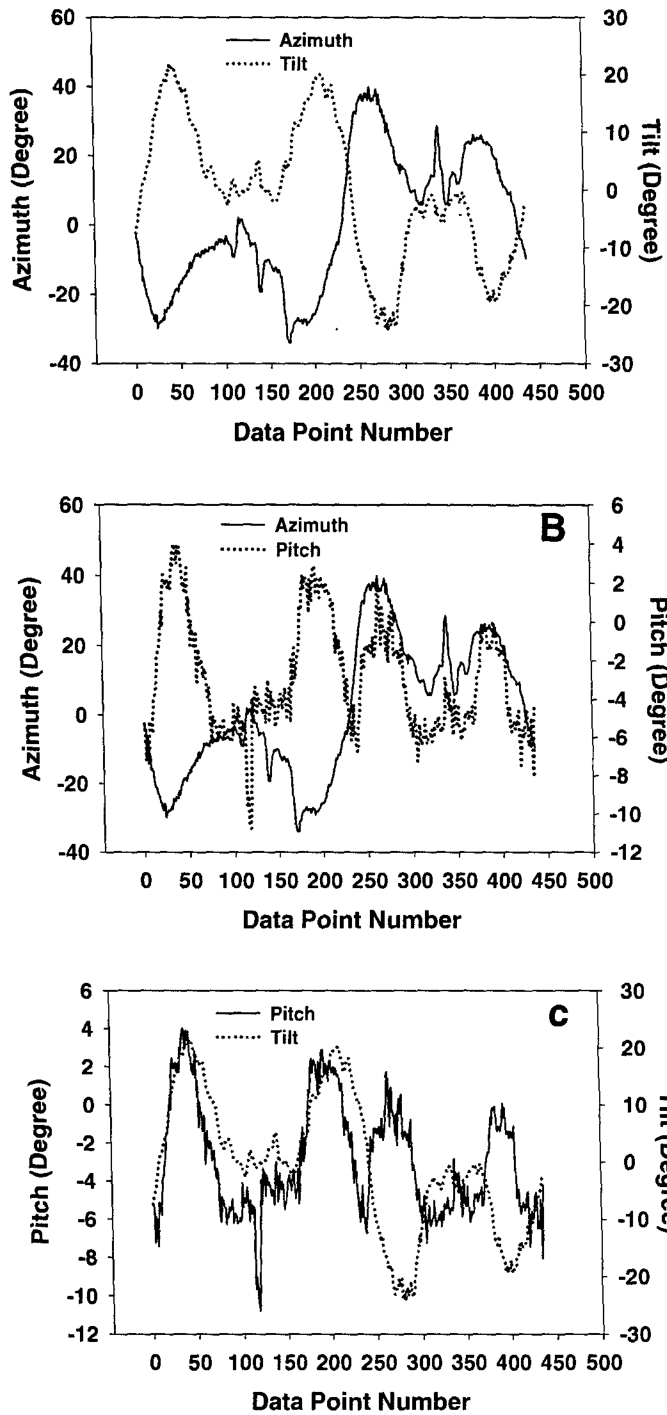



Figure A-9. Head position data from Flight 93, Pilot A's ninth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

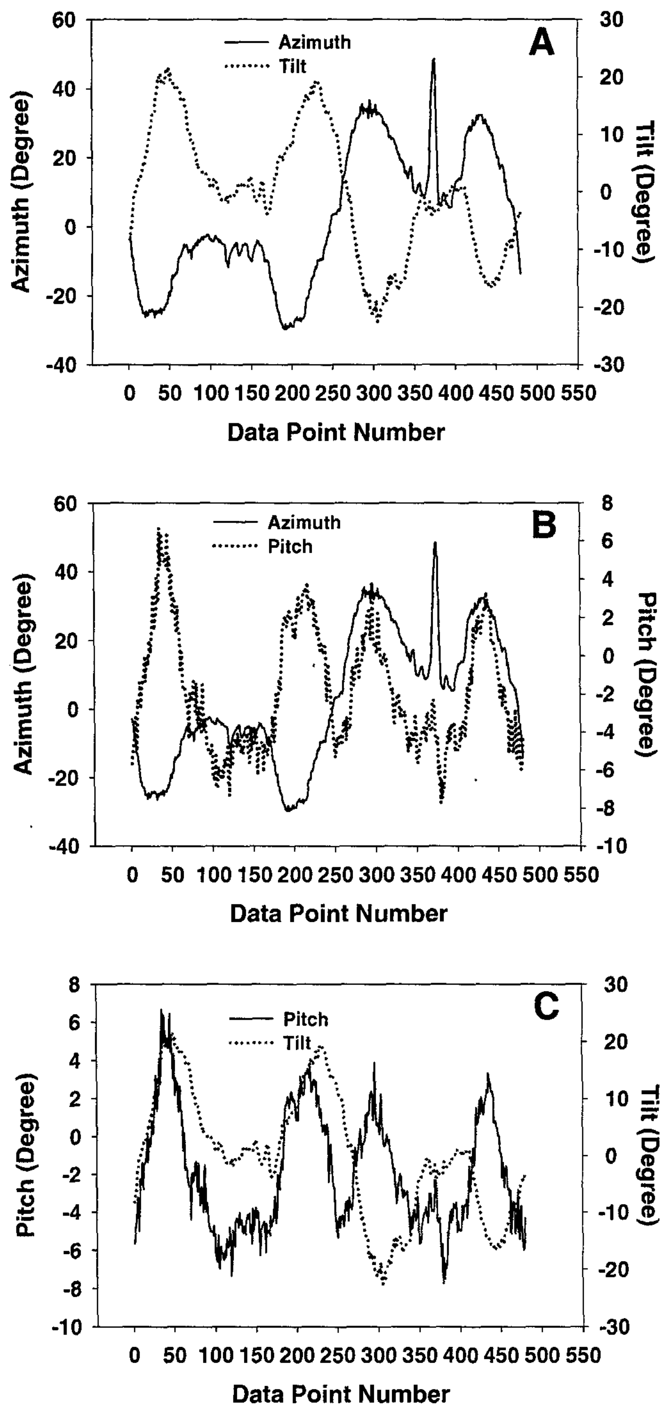



Figure A-10. Head position data from Flight 94, Pilot A's tenth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

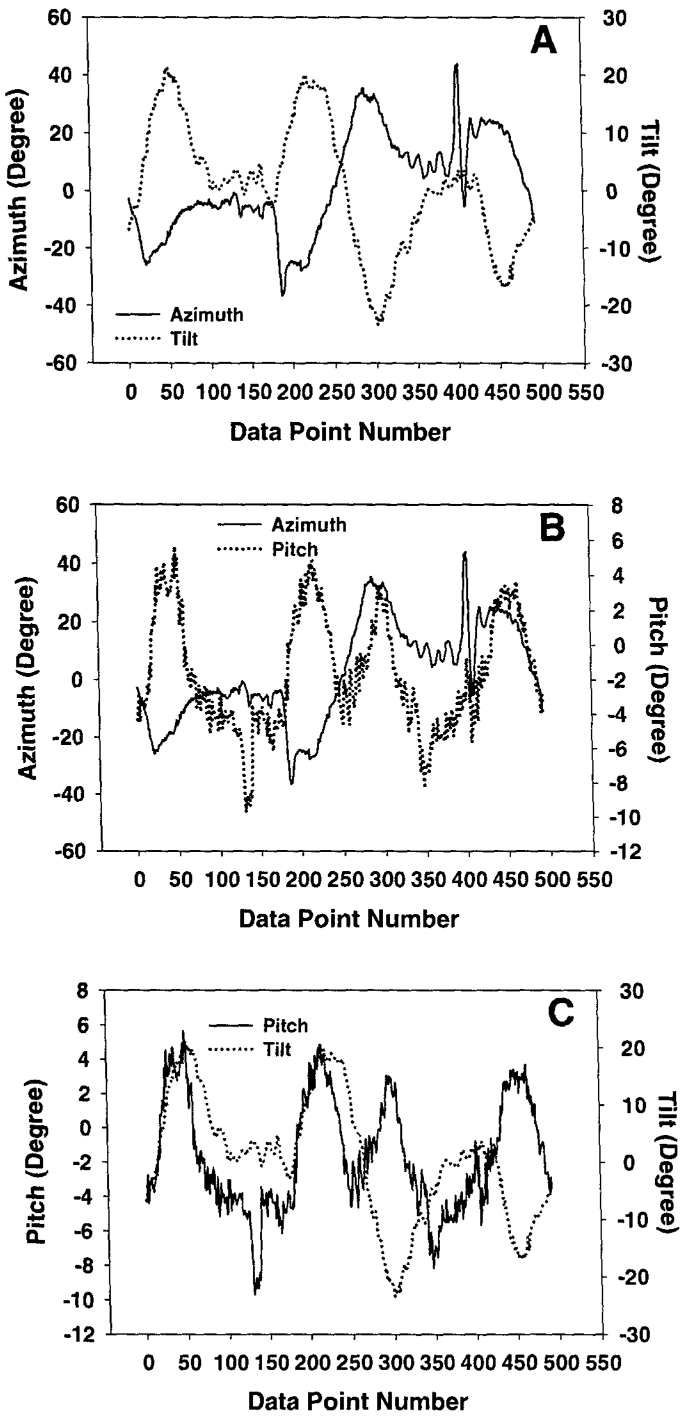



Figure A-11. Head position data from Flight 95, Pilot A's eleventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

## Appendix B.

Pilot B's head azimuth, pitch and tilt.

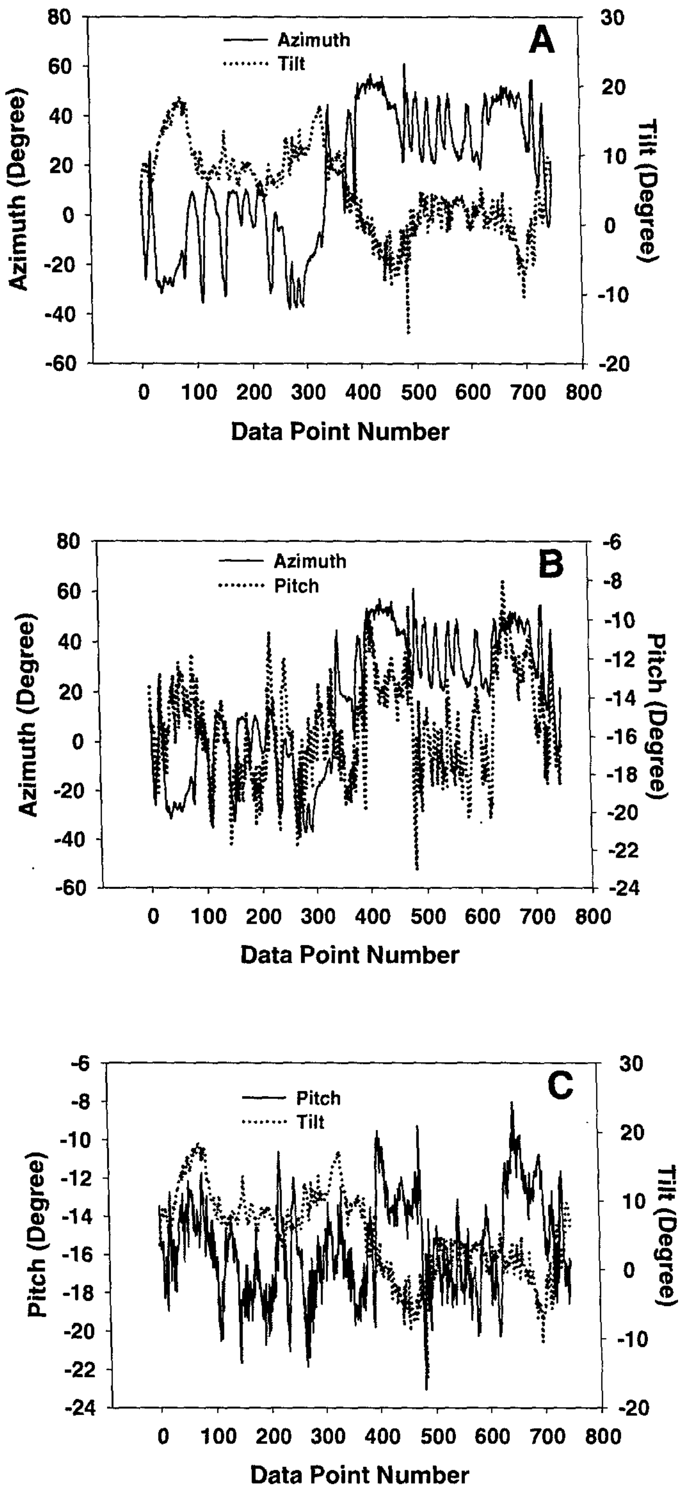



Figure B-1. Head position data from Flight 47, Pilot B's first flight, a low LOA slalom.
The format used here is the same as used in Figure A-1.

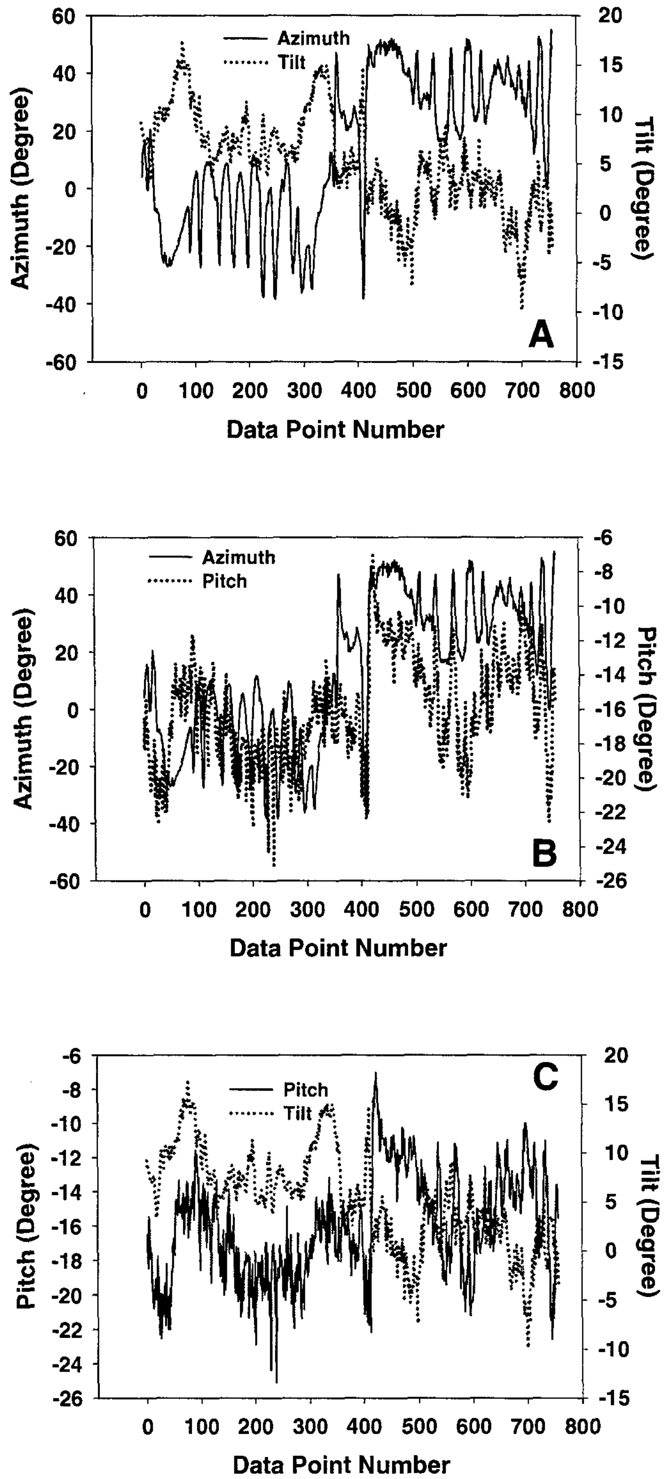



Figure B-2. Head position data from Flight 48, Pilot B's second flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

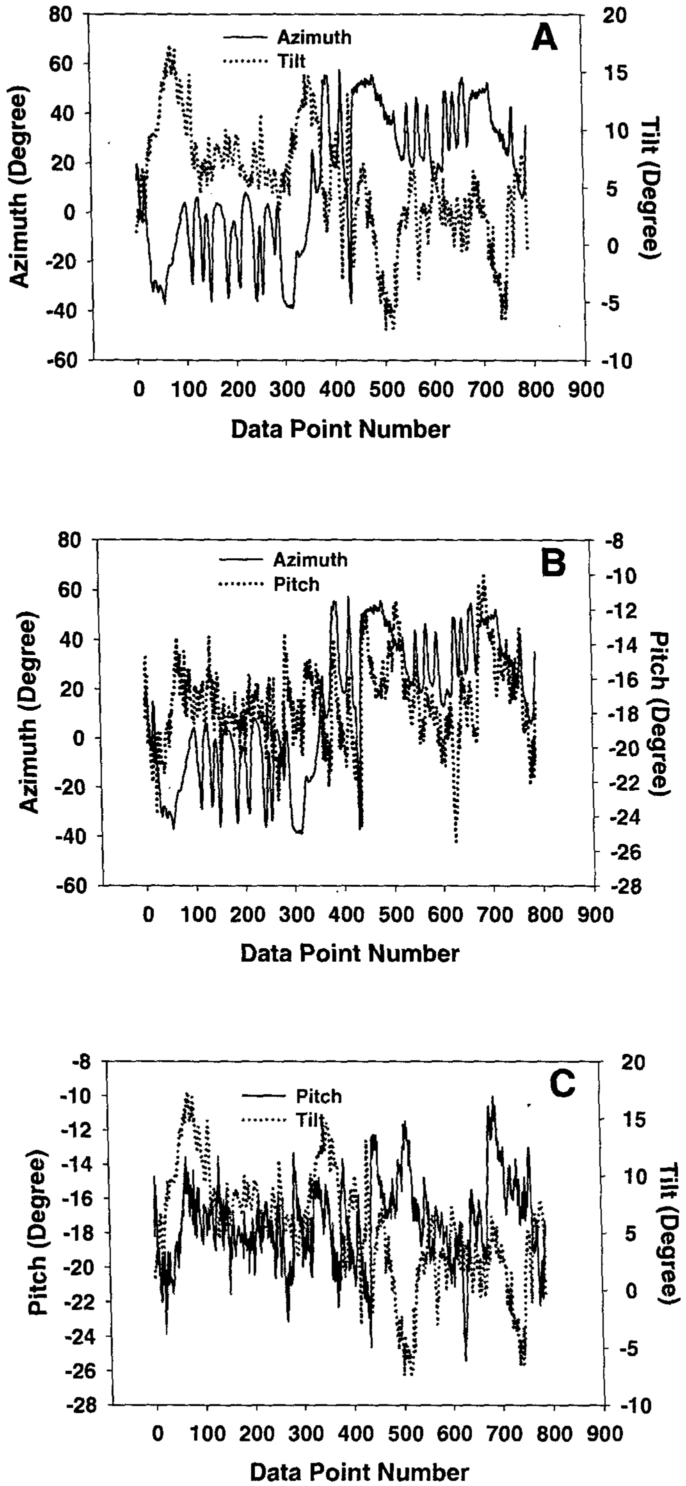



Figure B-3. Head position data from Flight 49, Pilot B's third flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

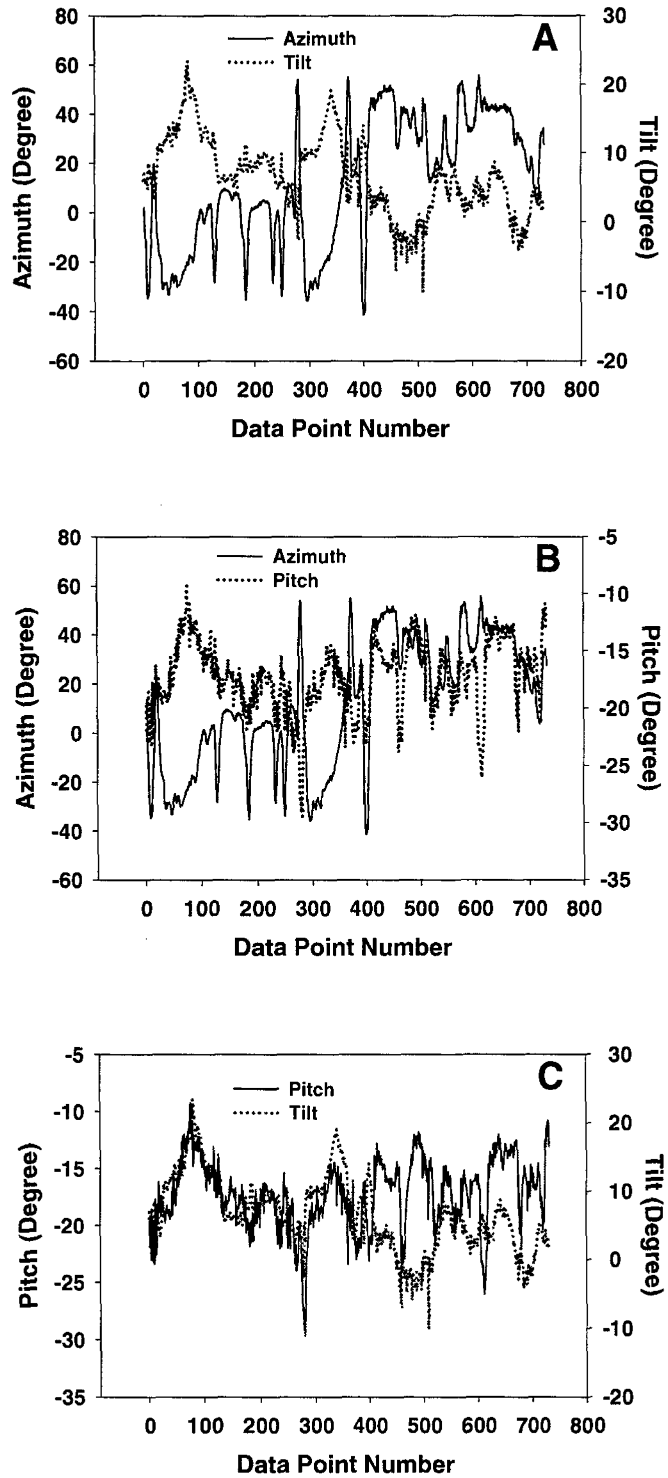



Figure B-4. Head position data from Flight 50, Pilot B's fourth flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

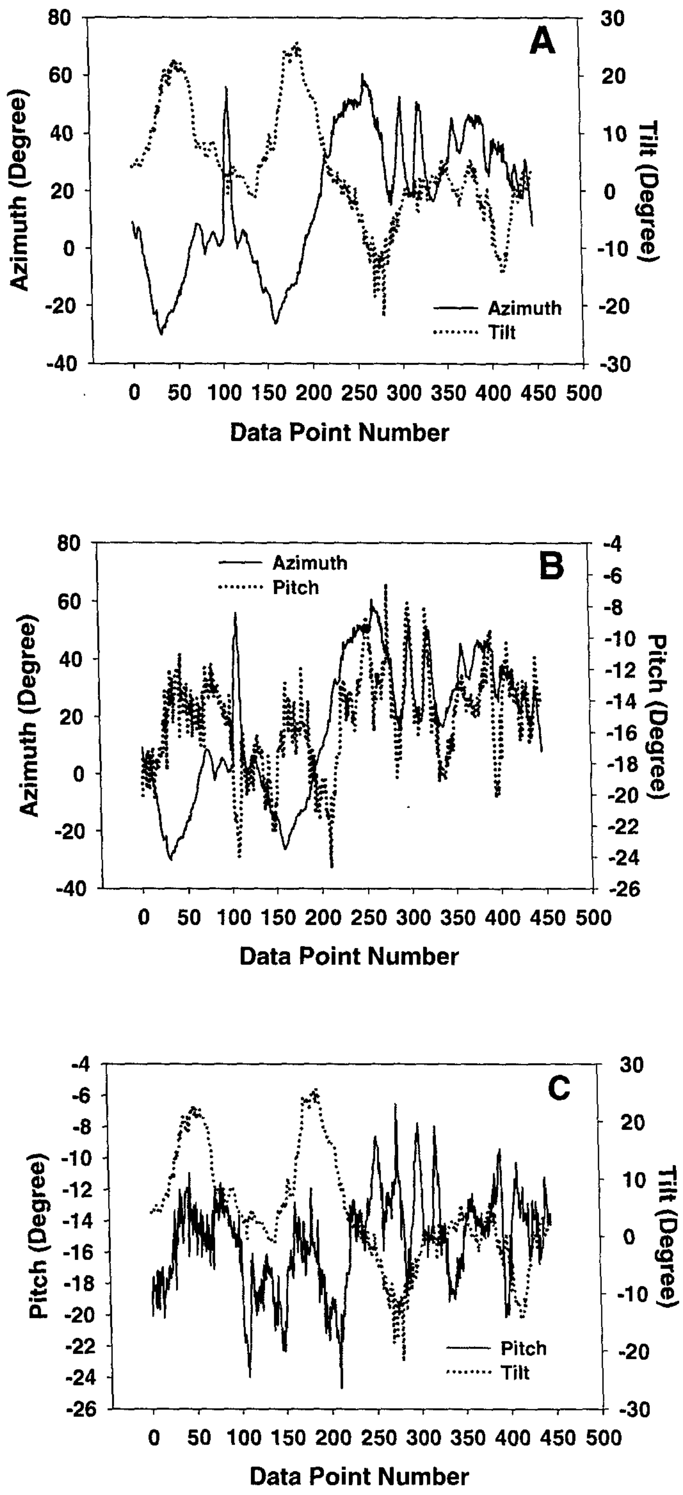



Figure B-5. Head position data from Flight 54, Pilot B's fifth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

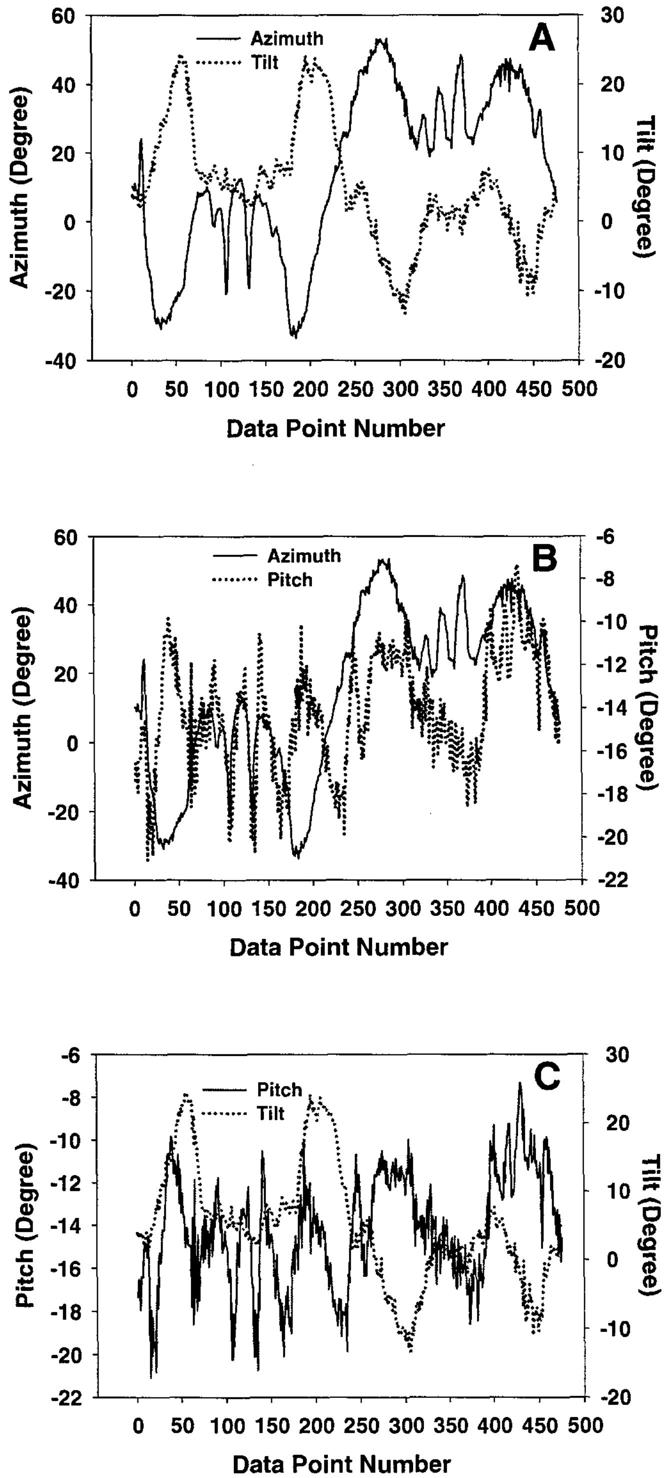



Figure B-6. Head position data from Flight 55, Pilot B's sixth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

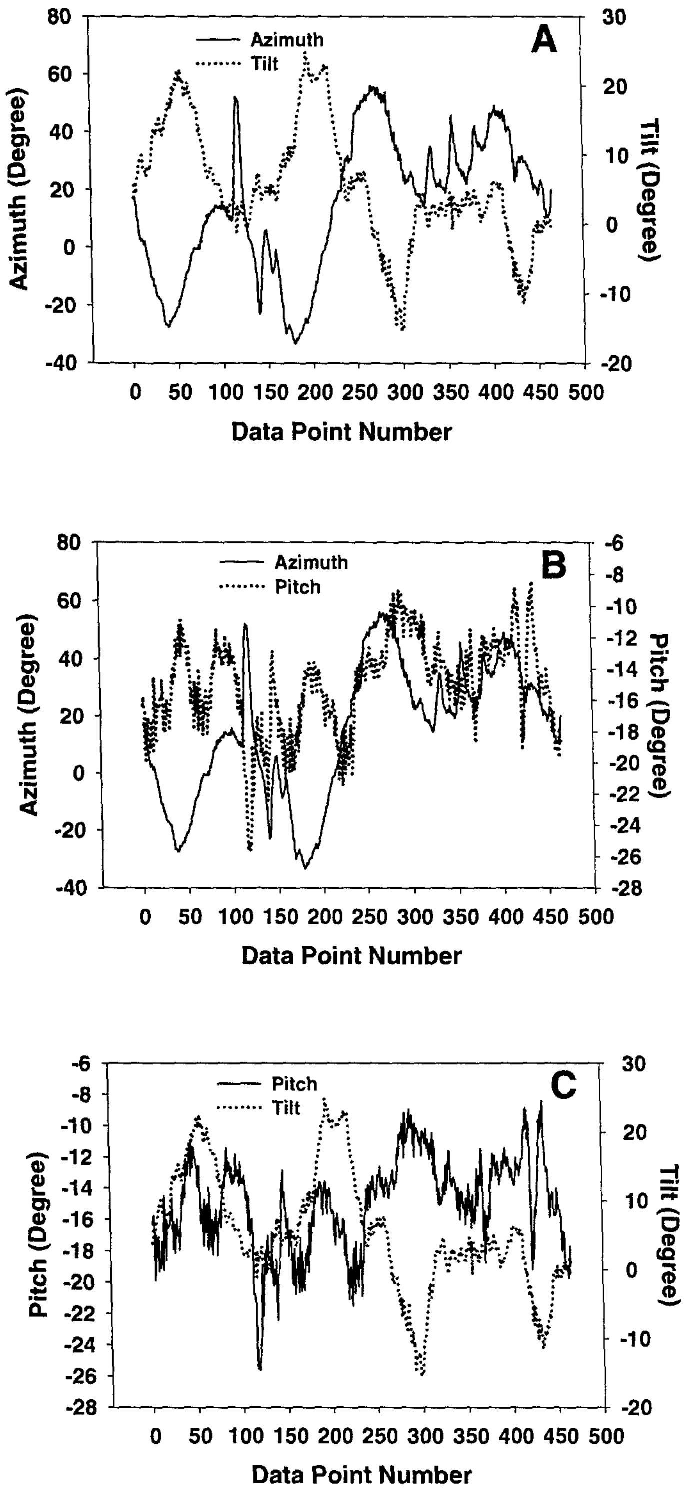



Figure B-7. Head position data from Flight 56, Pilot B's seventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

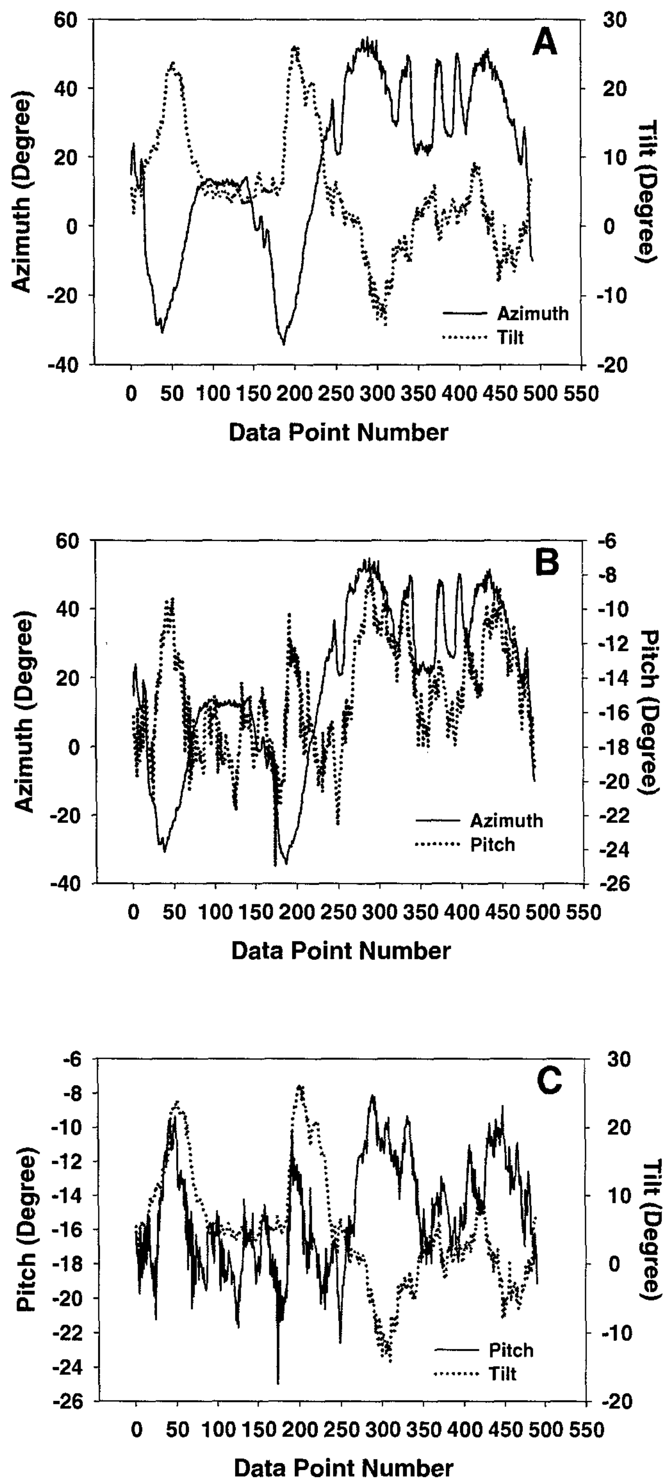



Figure B-8. Head position data from Flight 57, Pilot B's eight flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

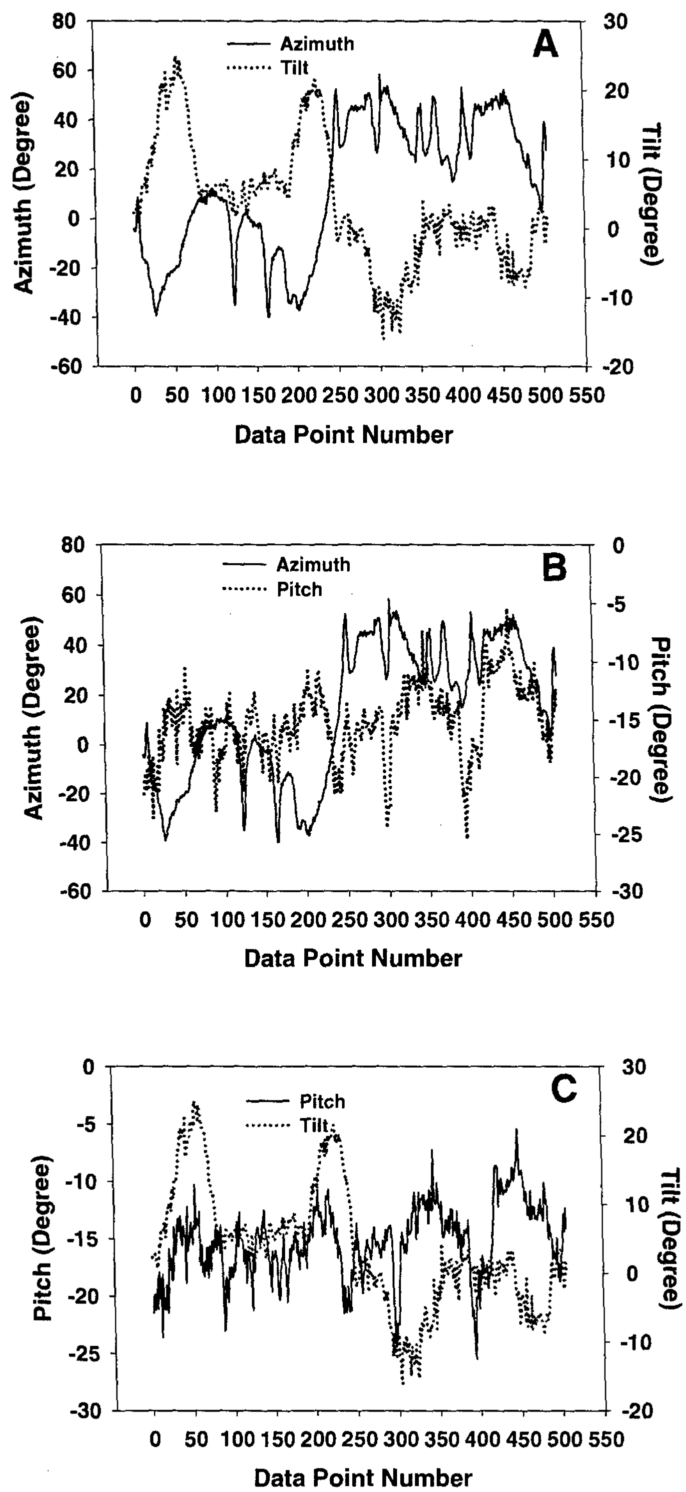



Figure B-9. Head position data from Flight 64, Pilot B's ninth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

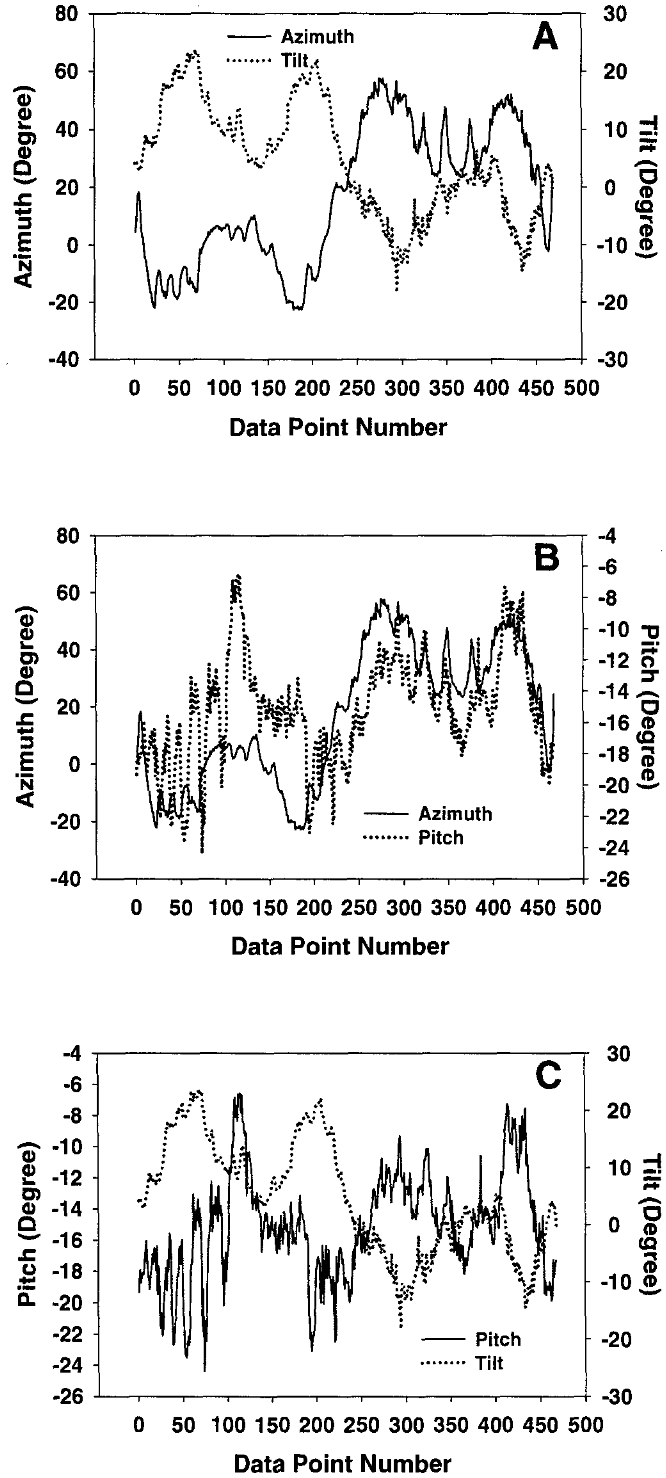



Figure B-10. Head position data from Flight 65, Pilot B's tenth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

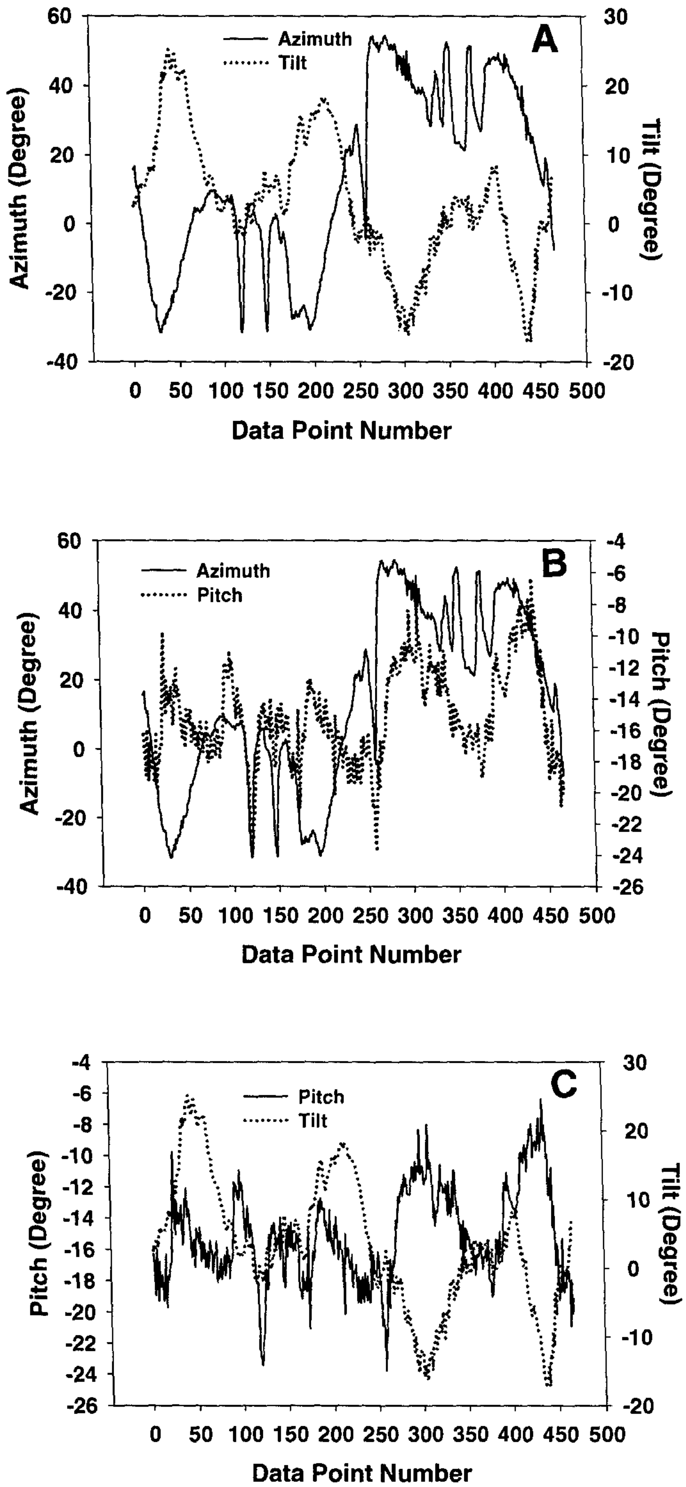



Figure B-11. Head position data from Flight 66, Pilot B's eleventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

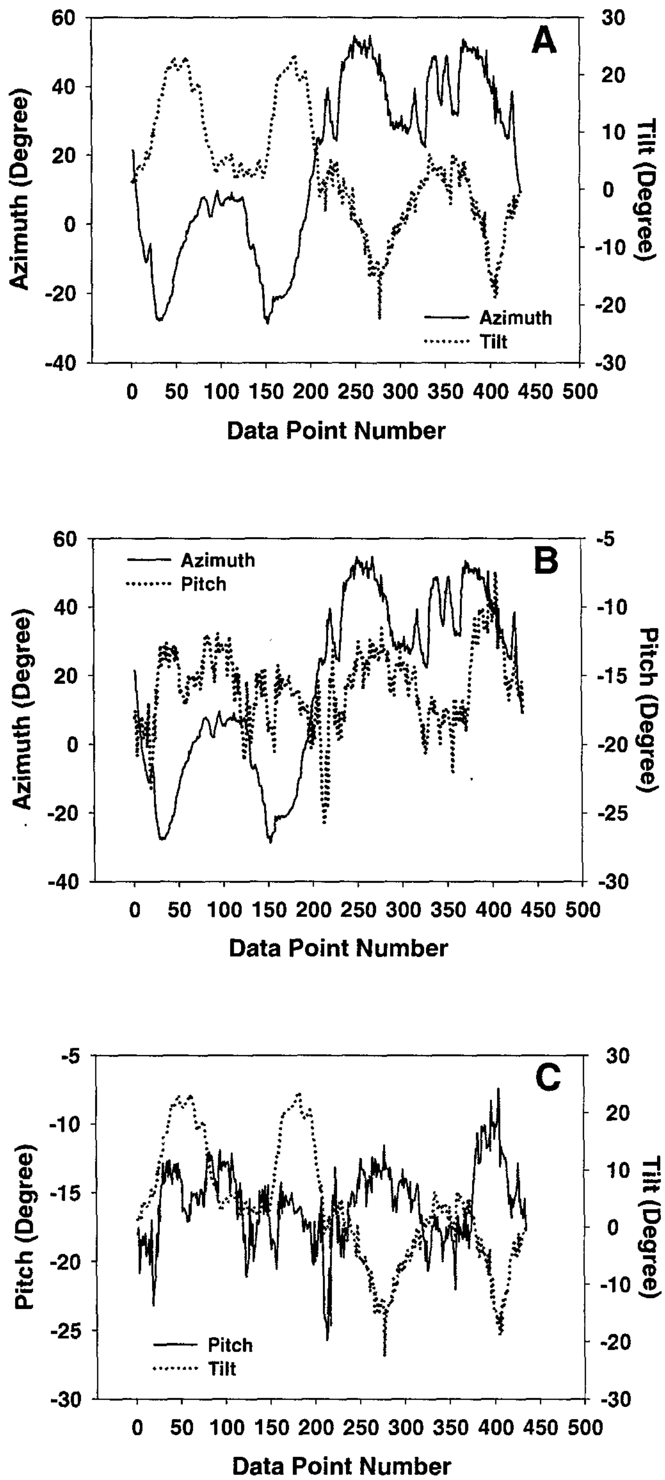



Figure B-12. Head position data from Flight 67, Pilot B's twelfth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

Appendix C.

Pilot C's head azimuth, pitch and tilt.

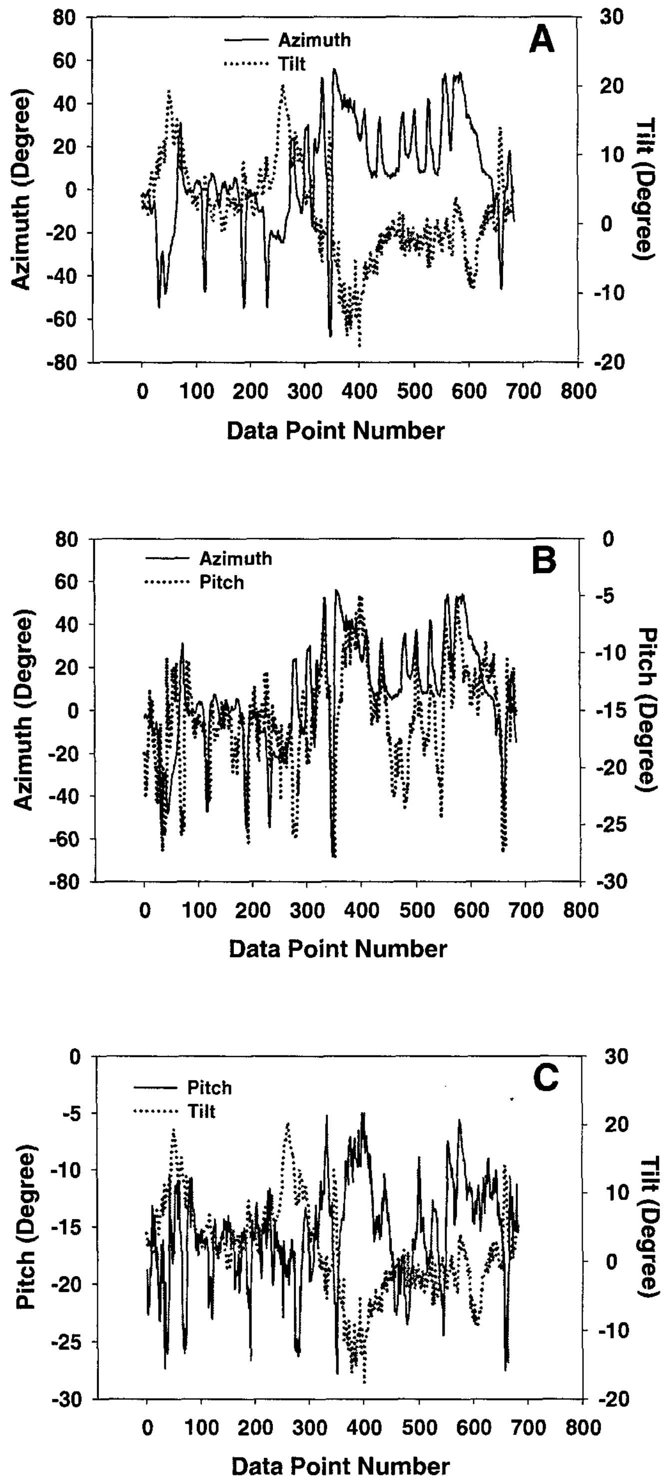



Figure C-1. Head position data from Flight 147, Pilot C's first flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

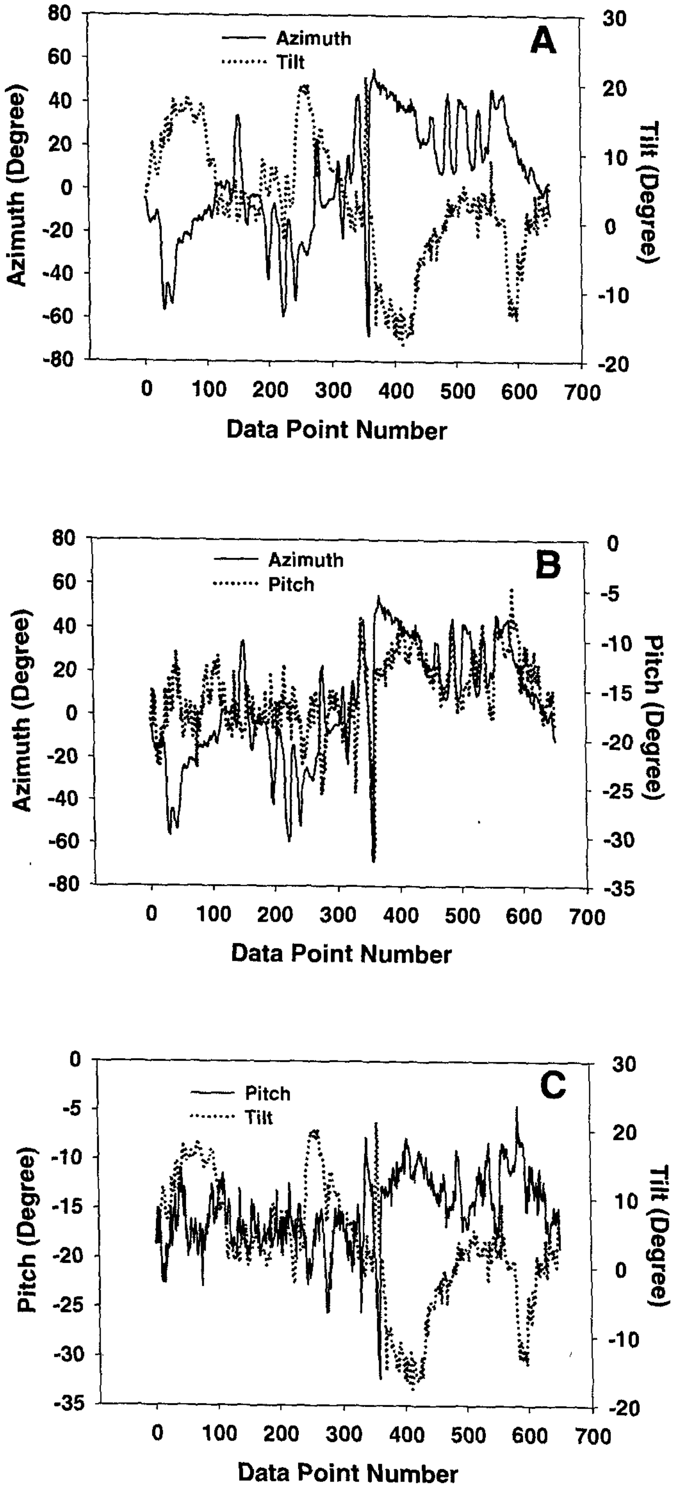
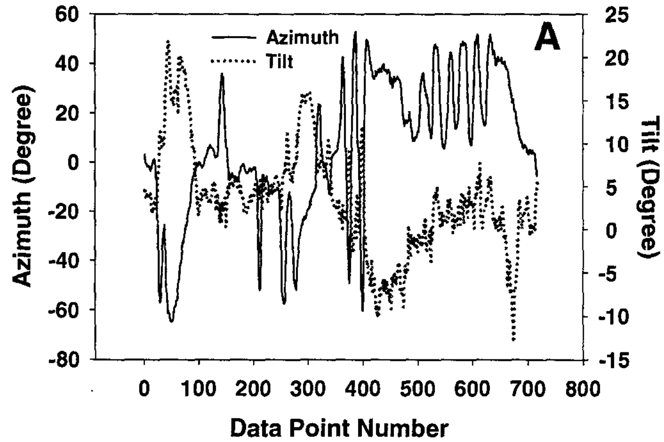
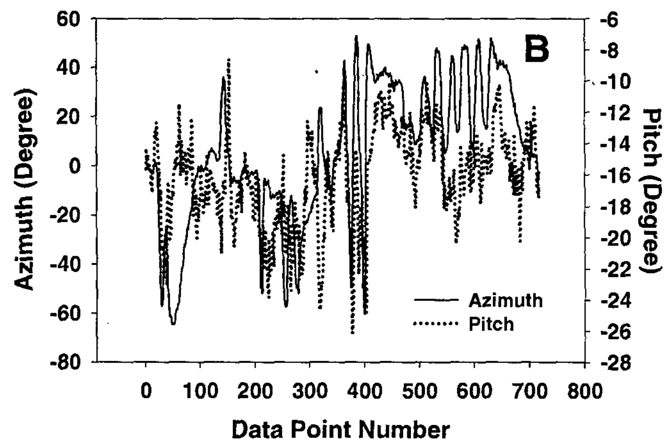



Figure C-2. Head position data from Flight 148, Pilot C's second flight, a low LOA slalom. The format used here is the same as used in Figure A-1.



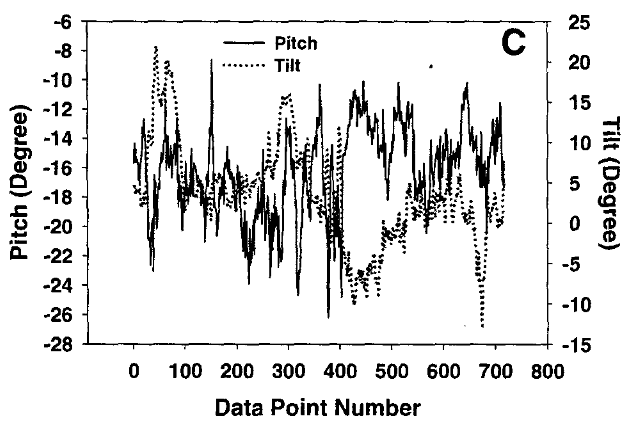




Figure C-3. Head position data from Flight 149, Pilot C's third flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

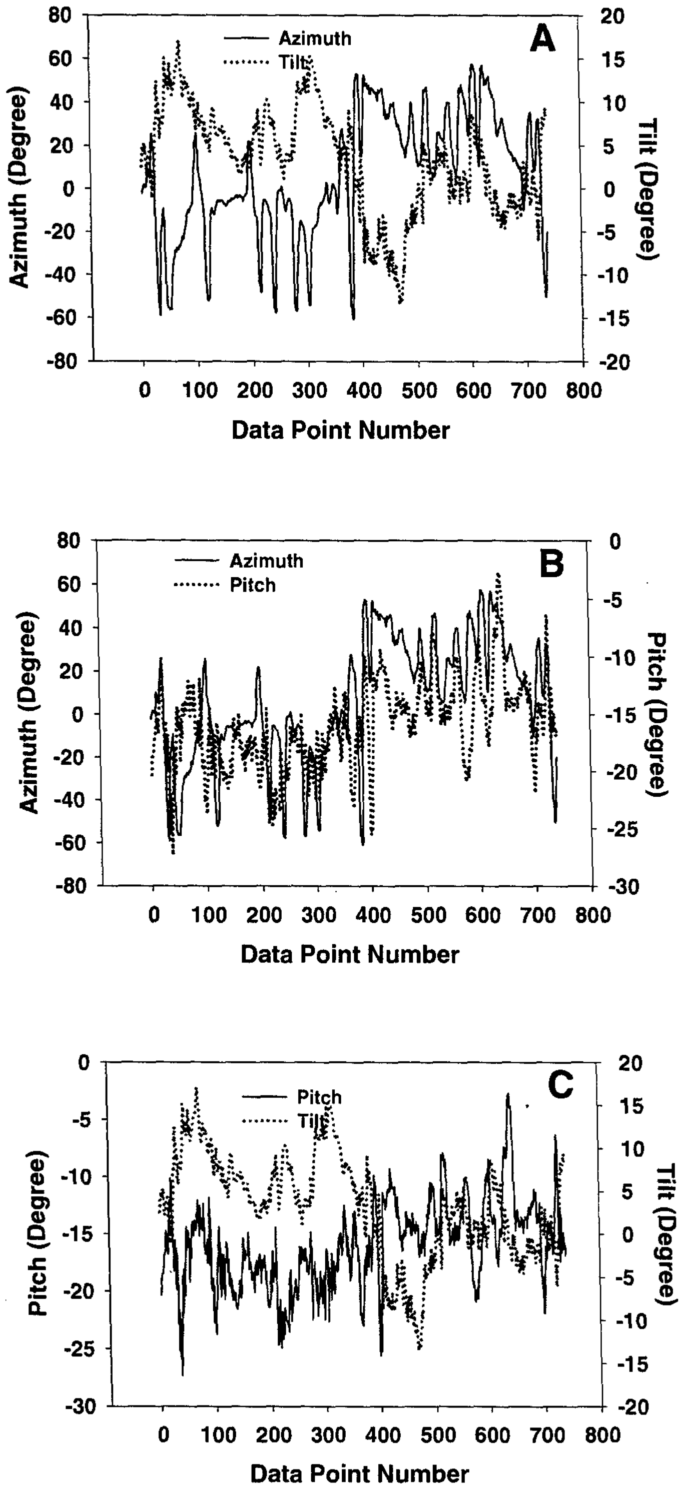



Figure C-4. Head position data from Flight 150, Pilot C's fourth flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

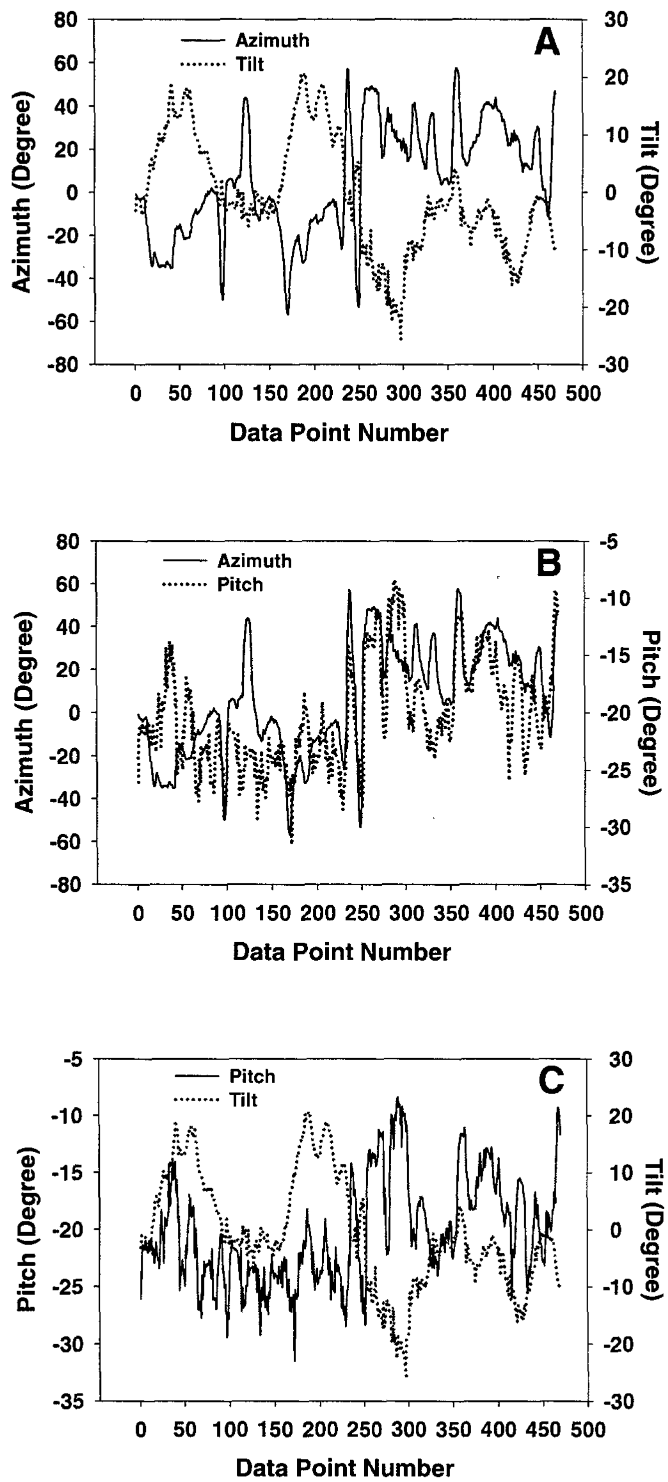



Figure C-5. Head position data from Flight 151, Pilot C's fifth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

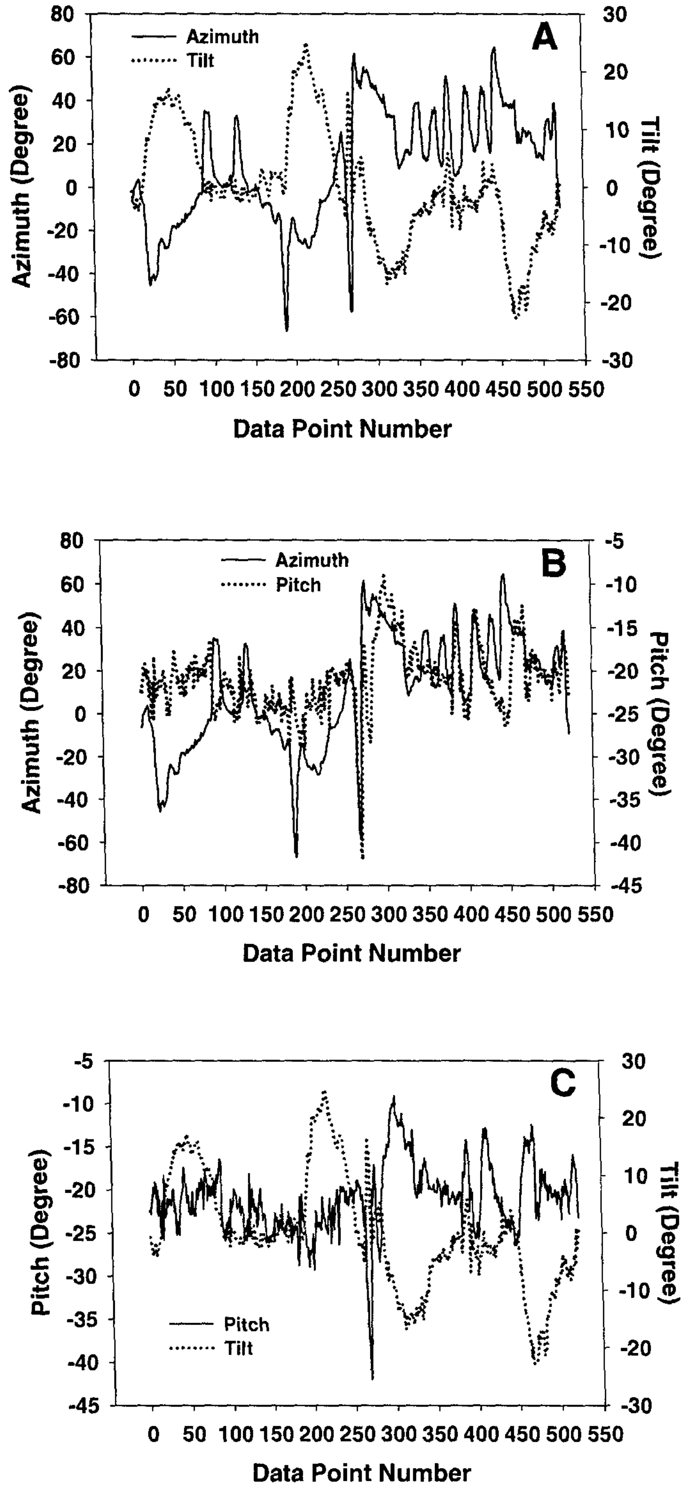



Figure C-6. Head position data from Flight 152, Pilot C's sixth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

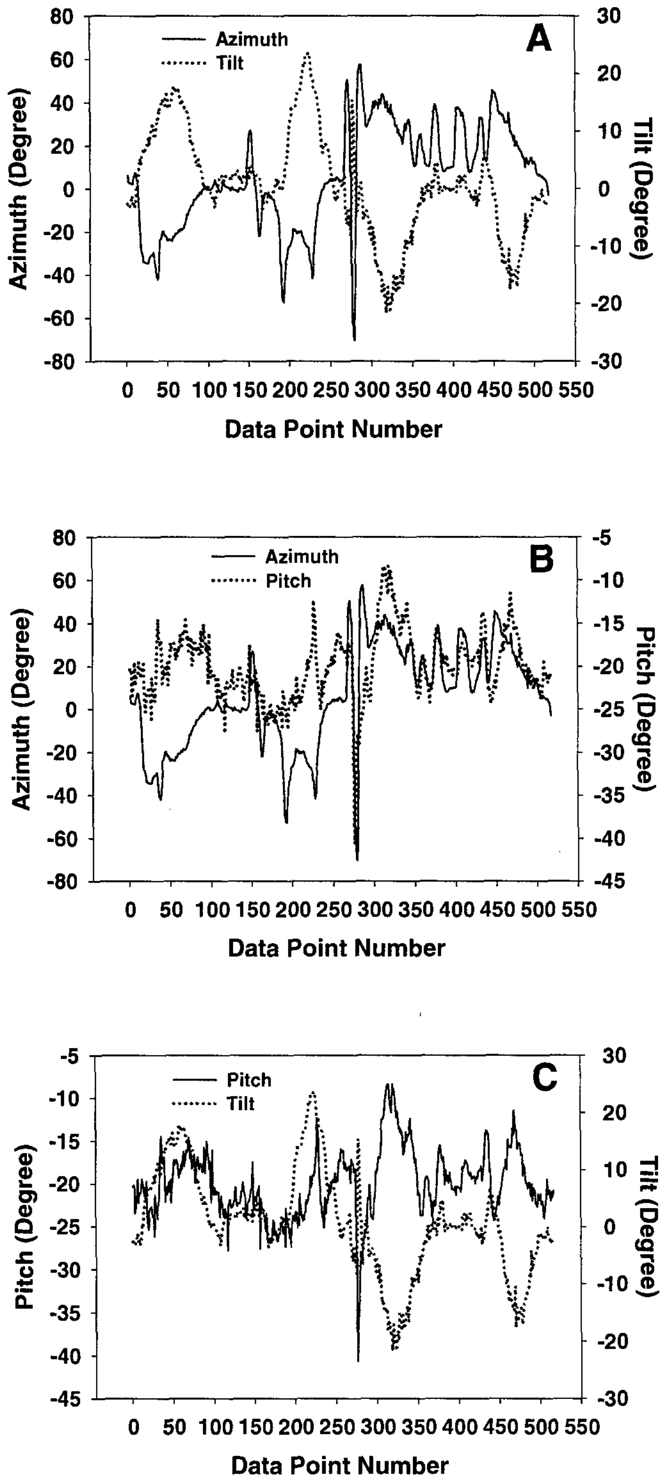



Figure C-7. Head position data from Flight 153, Pilot C's seventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

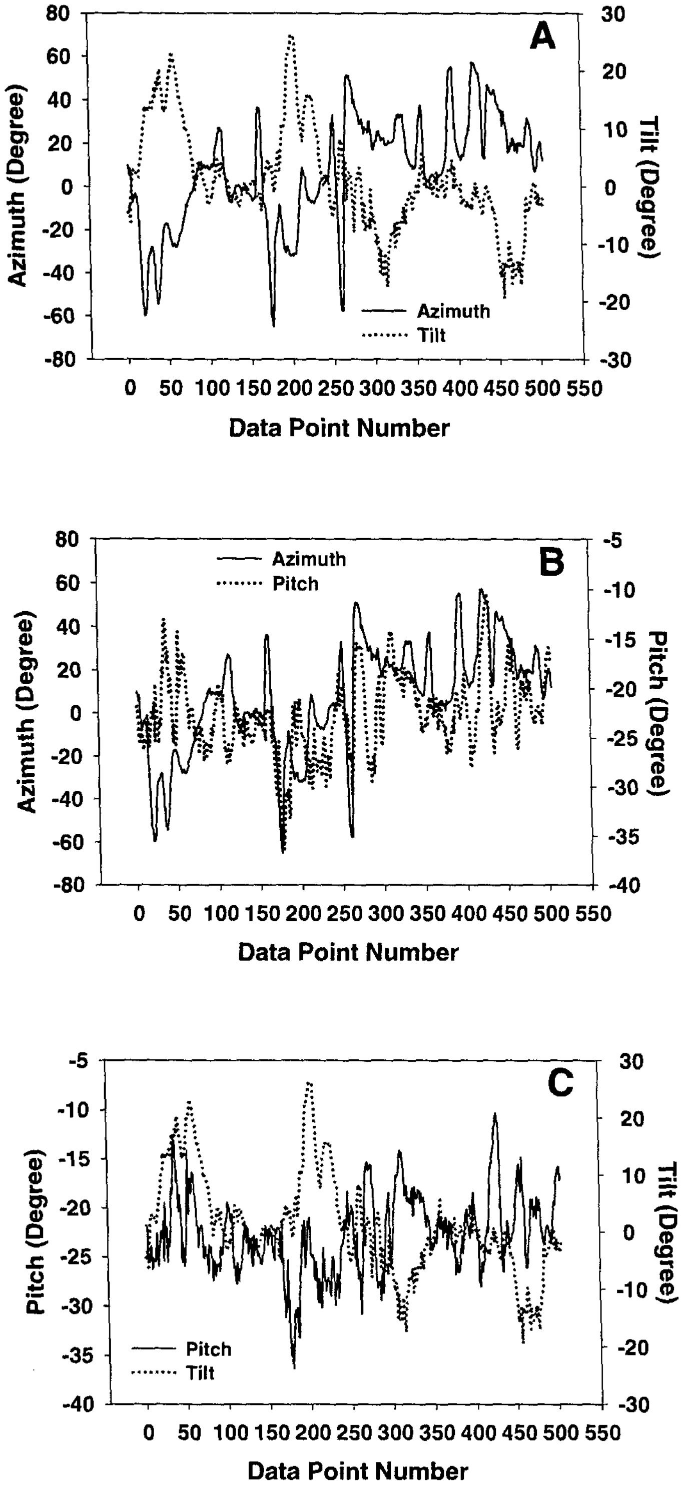



Figure C-8. Head position data from Flight 154, Pilot C's eighth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

Appendix D.

Pilot D's head azimuth, pitch and tilt.

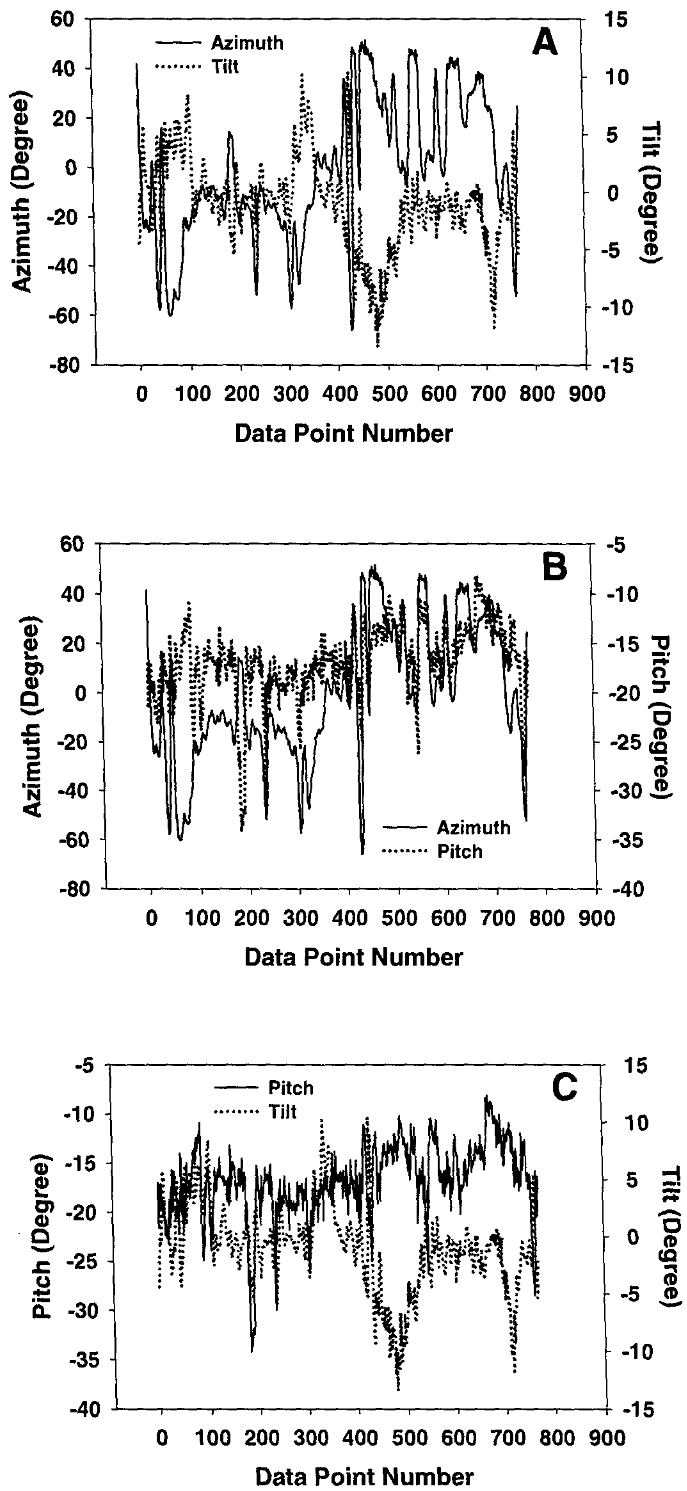



Figure D-1. Head position data from Flight 116, Pilot D's first flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

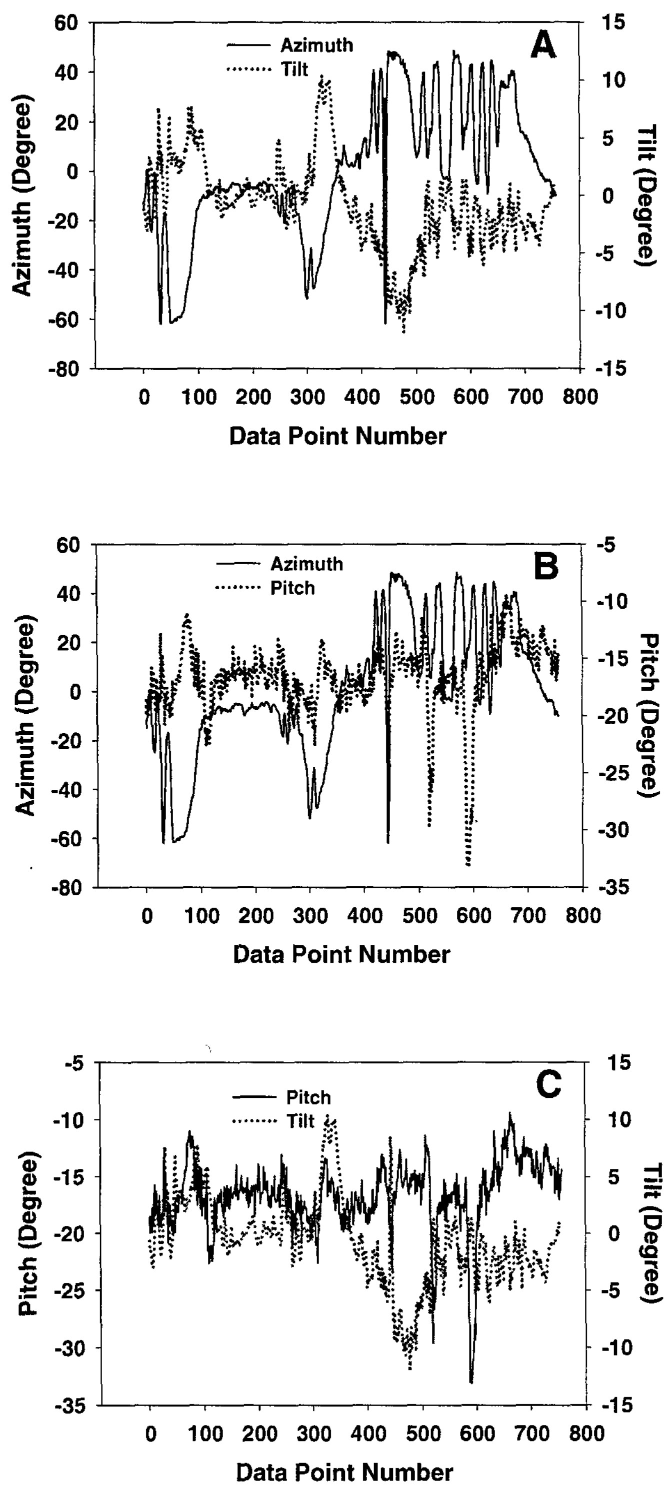
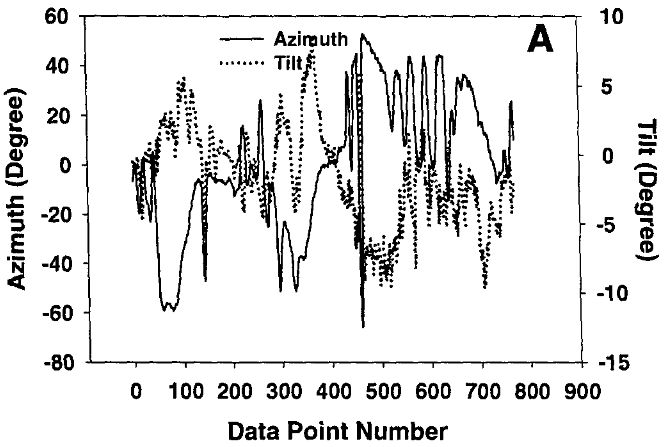
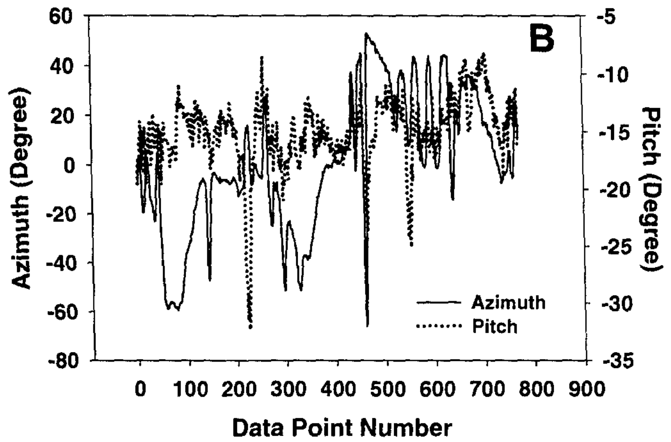



Figure D-2. Head position data from Flight 117, Pilot D's second flight, a low LOA slalom. The format used here is the same as used in Figure A-1.



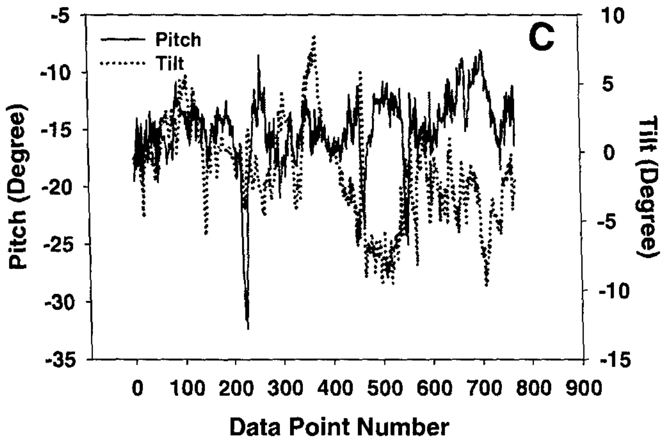




Figure D-3. Head position data from Flight 118, Pilot D's third flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

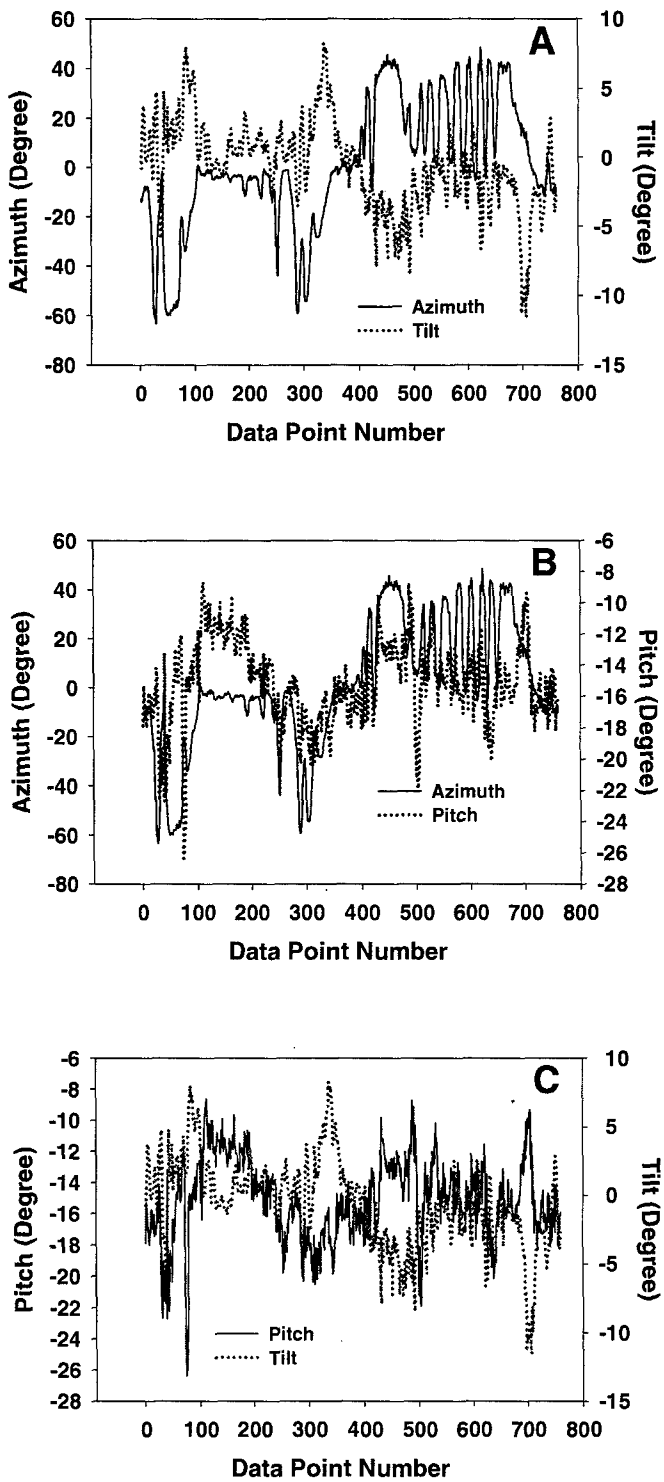



Figure D-4. Head position data from Flight 119, Pilot D's fourth flight, a low LOA slalom. The format used here is the same as used in Figure A-1.

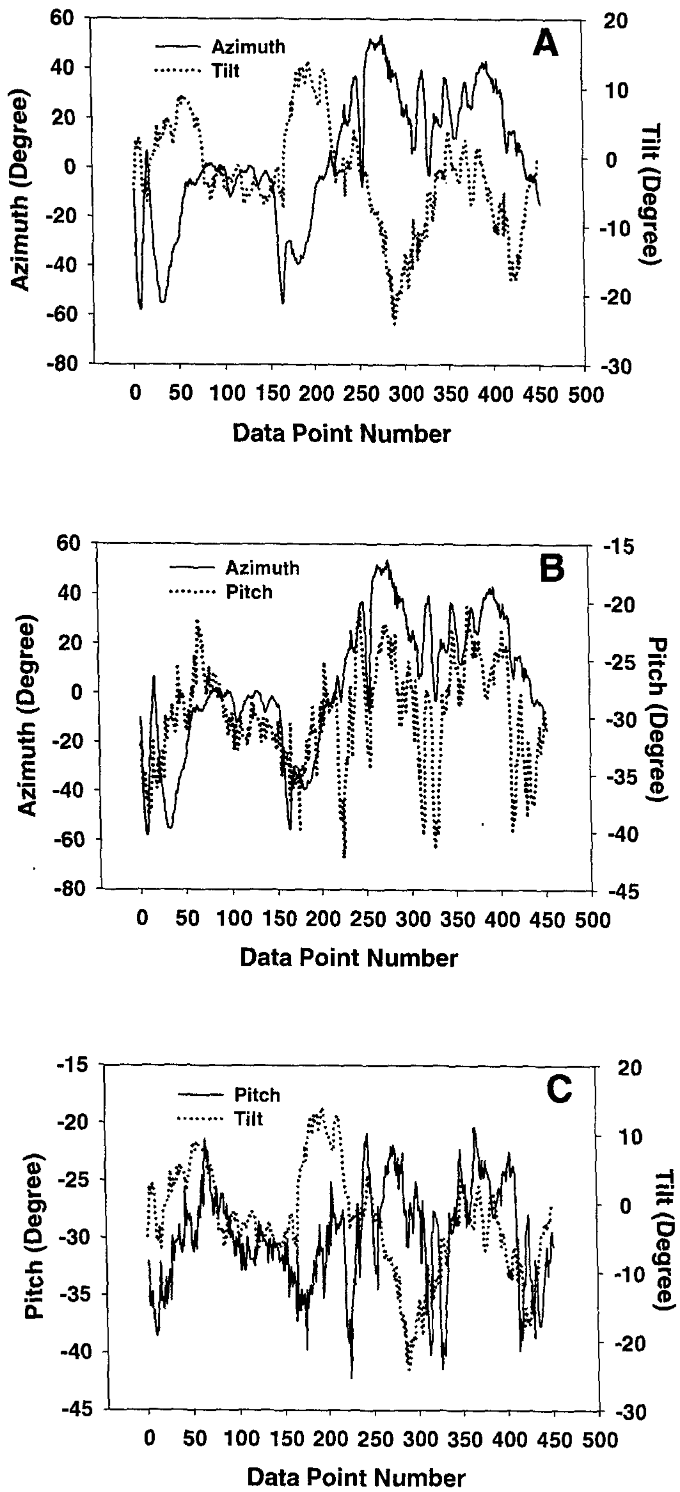



Figure D-5. Head position data from Flight 128, Pilot D's fifth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

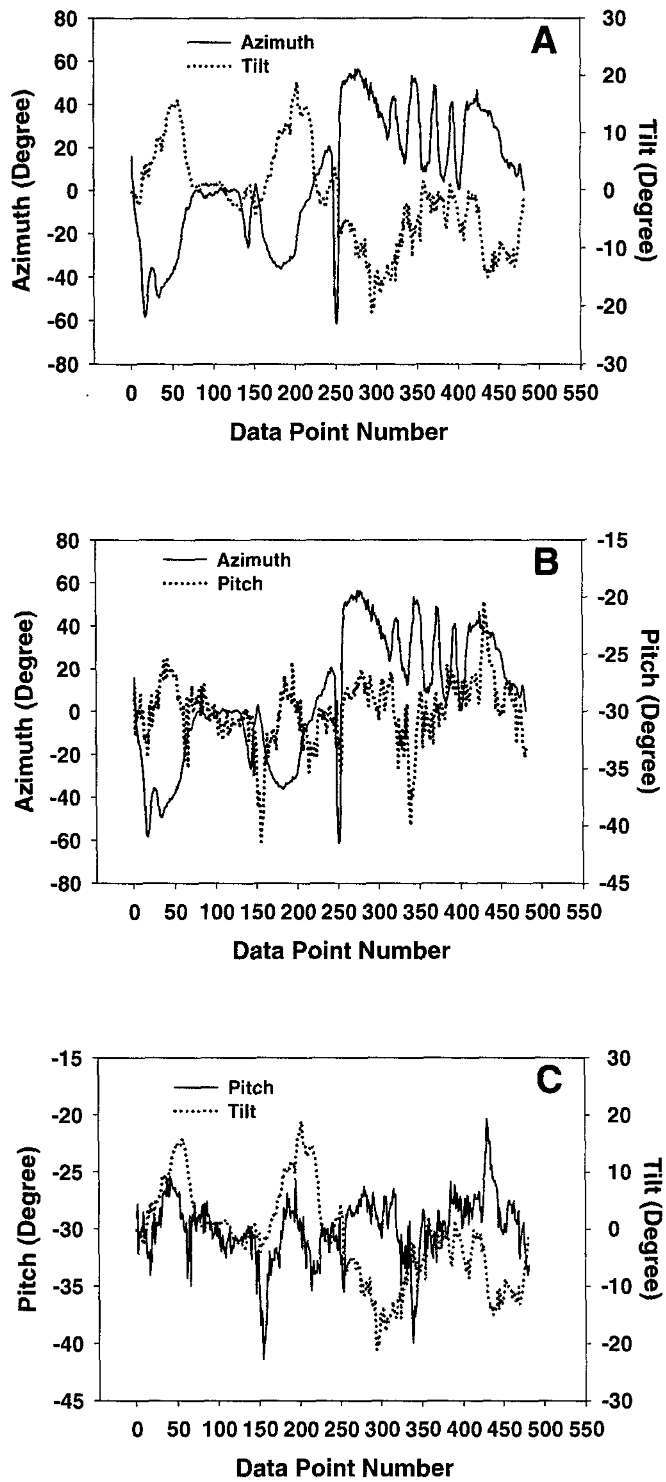



Figure D-6. Head position data from Flight 129, Pilot D's sixth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

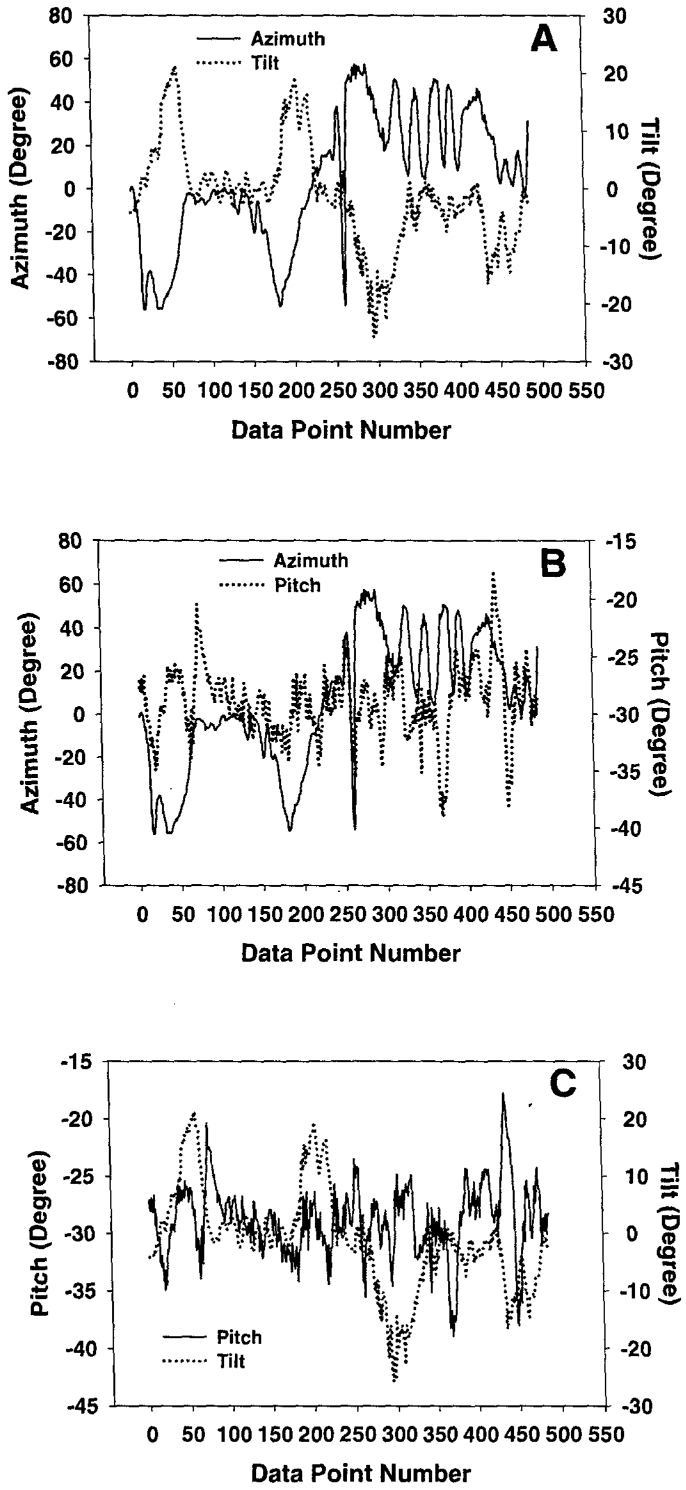



Figure D-7. Head position data from Flight 130, Pilot D's seventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

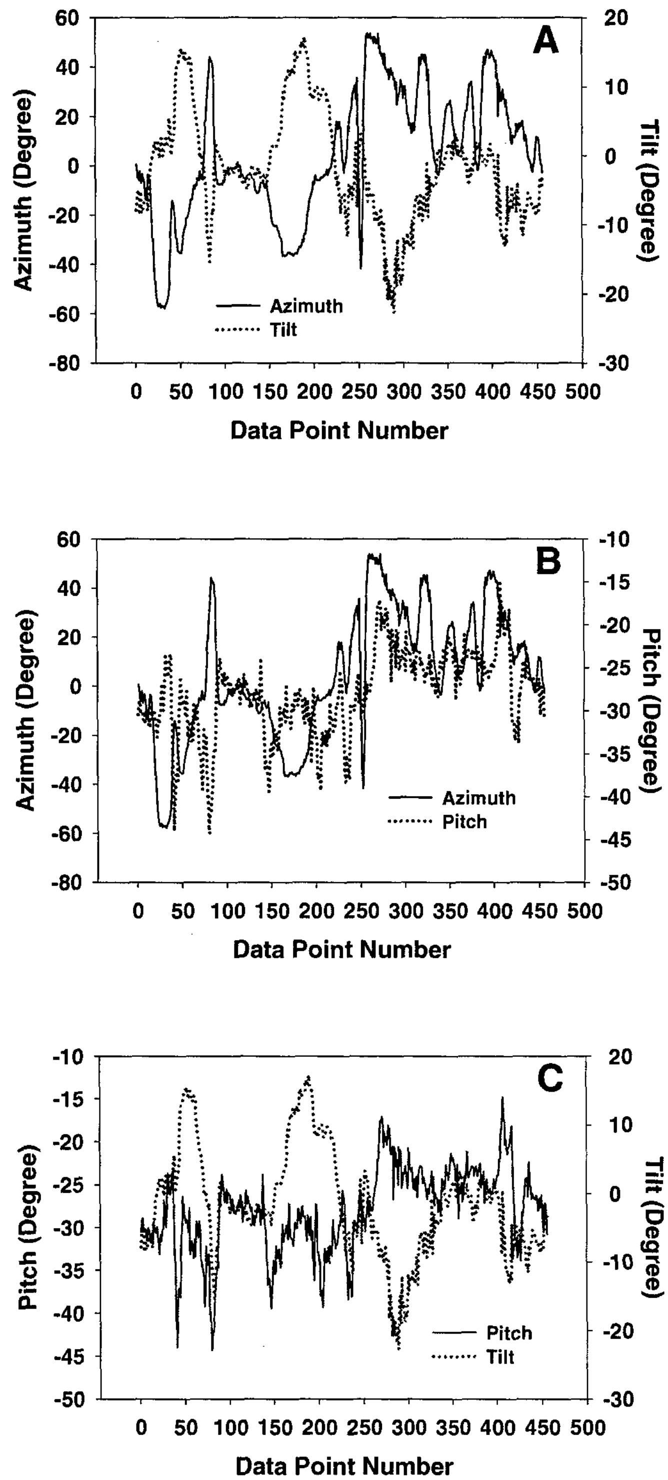



Figure D-8. Head position data from Flight 132, Pilot D's eight flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

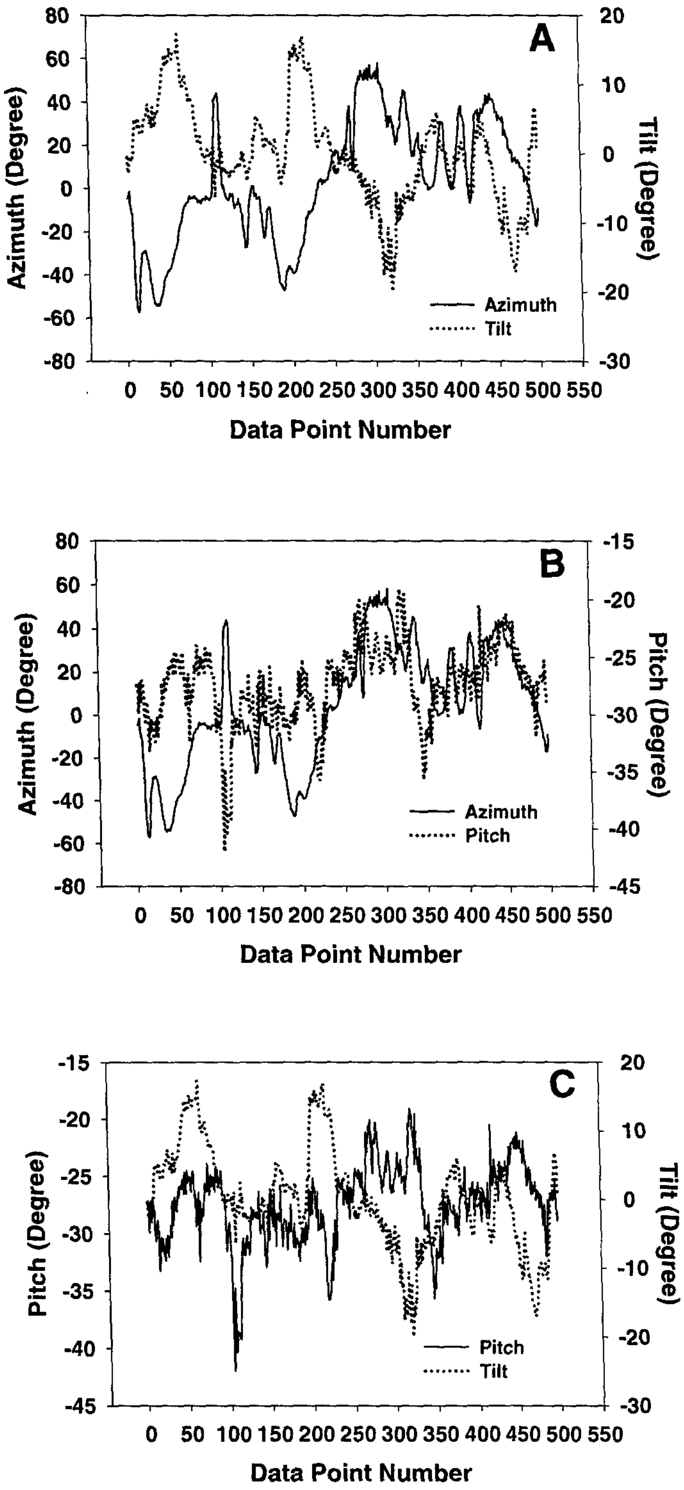



Figure D-9. Head position data from Flight 133, Pilot D's ninth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

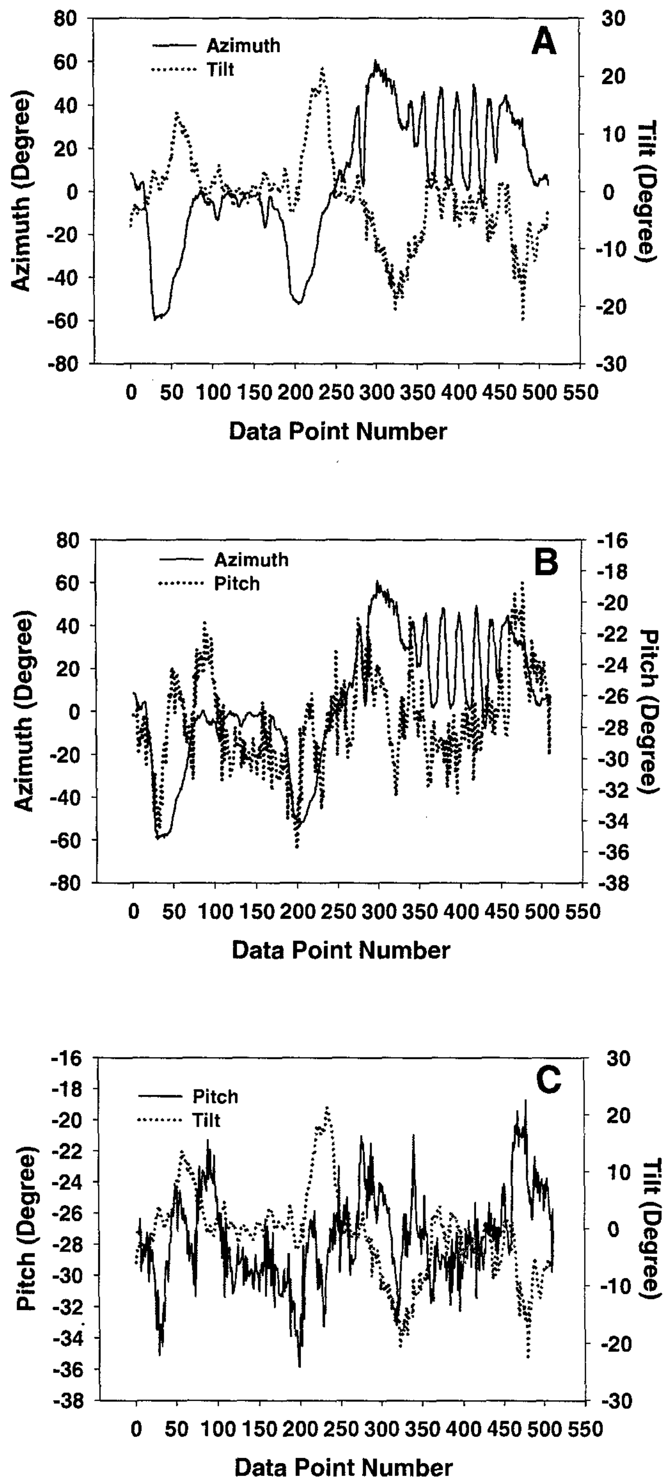



Figure D-10. Head position data from Flight 134, Pilot D's tenth flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.

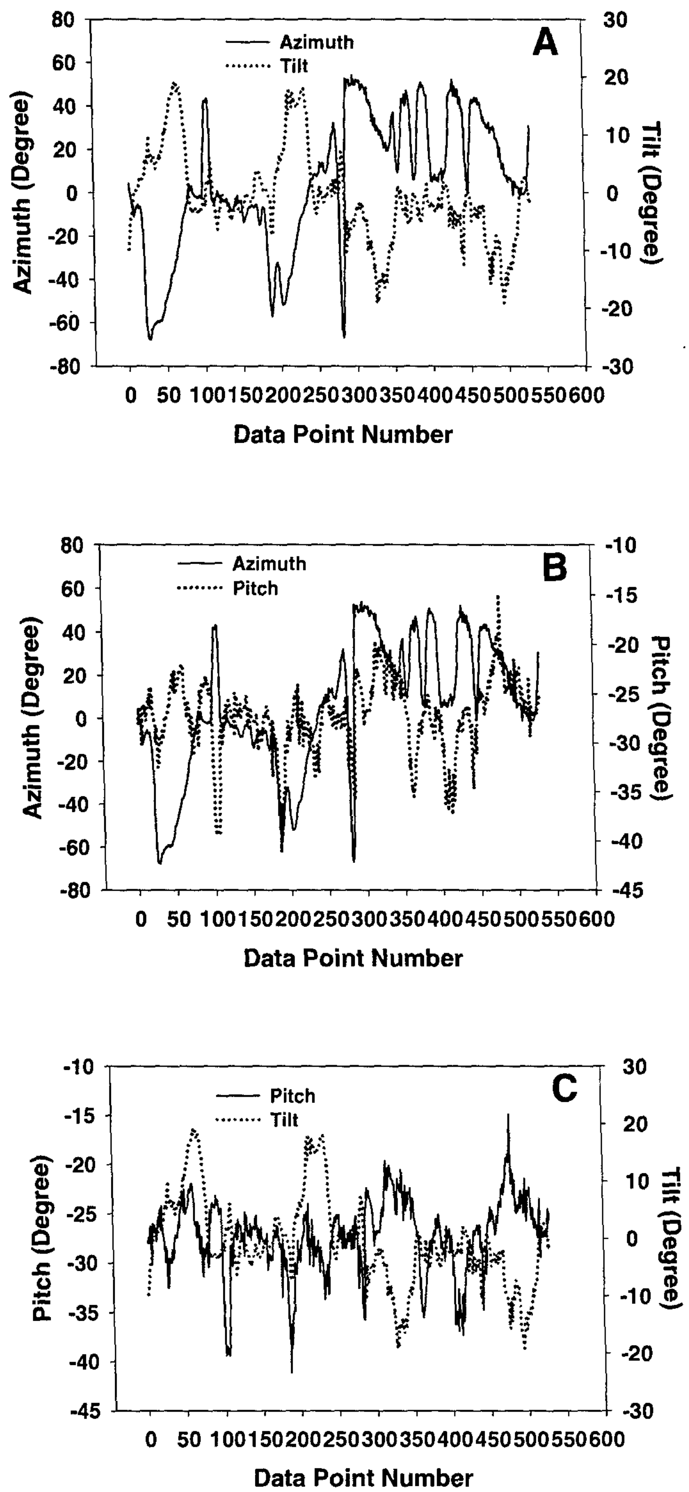



Figure D-11. Head position data from Flight 135, Pilot D's eleventh flight, a moderate LOA slalom. The format used here is the same as used in Figure A-1.